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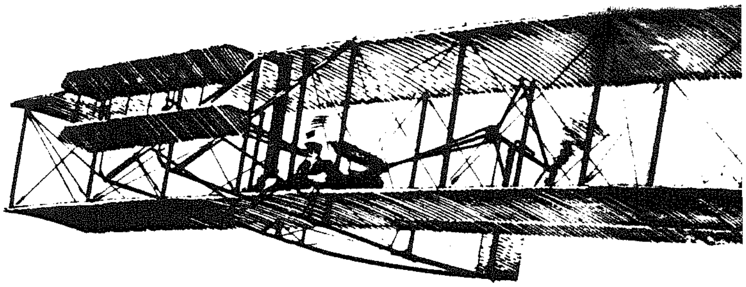

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"AERODYNAMICS, STABILITY AND CONTROL OF THE 1903 WRIGHT FLYER"

Fred E. C. Culick
Prof., Department of Aeronautics
California Institute of Technology
Pasadena, CA

Henry R. Jex
Principal Research Engineer
System Technology, Inc.
Hawthorne, CA 90250

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ABSTRACT

The Los Angeles Chapter of the American Institute of Aero and Astronautics is building two replicas of the 1903 Wright Flyer airplane; one to wind-tunnel test and display, and a modified one to fly. As part of this project the aerodynamic characteristics of the Flyer are being analyzed by modern wind-tunnel and analytical techniques. This paper describes the Wright Flyer Project, and compares key results from small-scale wind-tunnel tests and from vortex-lattice computations for this multi-biplane canard configuration. Analyses of the stability and control properties are summarized and their implications for closed-loop control by a pilot are derived using quasilinear pilot-vehicle analysis and illustrated by simulation time histories.

It is concluded that, although the Wrights were very knowledgeable and ingenious with respect to aircraft controls and their interactions (e.g., the good effects of their wing-warp-to-rudder linkage are validated), they were largely ignorant of dynamic stability considerations. The paper shows that the 1903 Flyer was readily controllable about all axes but was intrinsically unstable in pitch and roll, and it could barely be stabilized by a skilled pilot.

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Fred E. C. Culick

California Institute of Technology

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1. Introduction

The design, construction and flight of the 1903 ´Wright Flyer´* was a scientific engineering achievement of the first order. It´s true, as the Wright Brothers thoroughly appreciated, that their first powered flights were really only an intermediate success. They worked for two more years to improve their design until they had a practical airplane. But it is proper that we celebrate December 17, 1903 as the beginning of aviation. By then the Wrights had in hand practically all of the fundamental understanding and knowledge they needed to show the world how to fly.

Even by modern standards, the Wright Brothers´ program was extraordinarily well-conceived and efficiently executed. They conducted the necessary tests, collected only the data they needed, and generally carried on their work to learn just what

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*In a letter written on December 22, 1903, Bishop Milton Wright, father of the Wright Brothers, referred to their aircraft as the "Flyer" (Reference 1). This seems to be the earliest use of the name. Whether or not Bishop Wright intended to give the aircraft an "official" name is, we believe, immaterial. He used it, it´s a good name, and arguments as to its correctness, in some sense, seem pointless. We subscribe to Gibb-Smith´s usage (Ref. 2).

they required to succeed. Other papers in this collection will treat the Wrights' work on engines and structures. We restrict our discussion here to aerodynamics, stability, and flight control.

The following pages amount to a progress report covering contributions by many people. In 1953 members of the Los Angeles Section of the American Institute of Aeronautics and Astronautics constructed a reproduction of the 1903 'Flyer'. That airplane was destroyed in the fire at the San Diego Aerospace Museum in 1977; shortly after that event, the Los Angeles A.I.A.A. Section received the insurance claim. Mr. Howard Marx of the Northrop Corporation, as Chairman of the A.I.A.A. Committee on special events, proposed that a flying reproduction be constructed. The idea was enthusiastically supported and the A.I.A.A. Wright Flyer Project was born. We set out more than five years ago with dozens of people, to do by committee what the Wright Brothers alone did in less than four years! And we still haven't flown our 'Flyer'!

Our plans have expanded. We now intend to construct two reproductions. One is an accurate full-scale rendition of the 1903 'Flyer' to be tested in a wind tunnel. It is complete except for covering (Figure 1). The flying reproduction will incorporate small changes from the original design to make the aircraft easier to fly safely. Much of the material covered in this paper will serve as the basis for determining those changes. Equally important is our effort to interpret the Wrights' accomplishments in terms of the knowledge we have gained in the 80 years since their first flight.

We shall describe some of the results obtained from wind tunnel tests of two models, a 1/6 scale model tested at the California Institute of Technology, and a 1/8 scale model tested in a high speed tunnel whose owners will identify themselves at some later date. The data have been analyzed, partly with the help of some theoretical calculations performed at the Douglas Aircraft Company, to provide firm assessments of the stability and control of the 1903 'Flyer'. Using modern control theory, analyses carried out at Systems Technology, Inc. have helped us understand how the aircraft actually behaved when the Wright Brothers flew it. The results are particularly interesting for the controversial interconnected wing warp/rudder devised by the Wrights for lateral and directional control.

It was not a good airplane but it was by far good enough!

2. The Wrights' Wind Tunnel Data

Probably the best known scientific work by the Wrights is their program to obtain data for airfoils and wings. Theirs was not the first wind tunnel - which was invented in England, by Wenham and Browning in 1877 (Reference 3) - nor were theirs the first wind tunnel data obtained in the United States. Albert C. Wells measured the correct value for the drag coefficient of a flat plate, reported in his thesis submitted to the Massachusetts Institute of Technology in 1896 (Reference 4). Wells converted a ventilation duct for his work; the Wrights designed and built a small open circuit tunnel. With that device, during three months in 1901 they took the first extensive systematic data suitable for the design of aircraft. The results served them well for a decade.

Ten years earlier, Otto Lilienthal had used a whirling arm apparatus to measure the lift and drag for various airfoils approximating the shape of birds' wings (Reference 5). The Wright Brothers used his data in the design of their 1900 and 1901 gliders. It is a familiar fact that because they obtained substantially less lift with their gliders than they had predicted with Lilenthal's results, the Wrights resolved to obtain their own data. What is less well-known is that in the course of their program they determined that Lilientahl's data were essentially correct.

The difficulty lay with the value of a coefficient which was required to convert Lilienthal's numbers to obtain the actual aerodynamic forces acting on a wing. That coefficient - the drag force acting on a unit area of plate oriented perpendicular to a stream moving with speed one mile per hour - was called Smeaton's coefficient.

John Smeaton was the pre-eminent English civil engineer of the 18th century. In 1759 he published an important memoir (Reference 6) in which he discussed theory and experiment for the fluid mechanics of water wheels and windmills. He included a table of data, provided by a Mr. Rouse, from which the coefficient defined above can be deduced and shown to be approximately 0.0049, independent of velocity. Thus the drag on a plate having area S in a stream moving at speed V (MPH) is

$$D = 0.0049\ V^2\ S \qquad (1)$$

The value 0.0049 is for air, being proportional to the density of the medium. Presumably because of his stature and because he authored the book, Smeaton's name was subsequently attached to this number. Mr. Rouse, who did the work, has hardly ever since been cited.

In any case, this value of Smeaton's coefficient persisted for 150 years. The strength of tradition caused Liliental to accept the value without question. But the Wrights determined otherwise. With a clever combination of their wind tunnel data and a few tests with a wing from their 1901 gliders, they concluded that the correct value was 0.0033 which is now known to be correct for the range of speeds in which they were working. Langley (Reference 7) had previously found this result, confirmed later by Wells.

Figure 2 shows the close agreement between the measurements of Lilenthal and those of the Wrights for the same parabolic airfoil. They are expressed here in the modern terms, lift coefficient (lift force divided by the dynamic pressure and area) as a function of the angle of incidence between the flow and the airfoil. The shift of the Wrights' view from their initial belief that Liliental's data was seriously in error, to the recognition that their own results agreed with his, is a superb illustration of the objective and thoroughly professional fashion in which they carried out their work. The following selections from Wilbur's diary (Reference 1) summarize the development of their views.

<u>October 6, 1901</u>

"I am now absolutely certain that Liliental's table is very seriously in error, but that the error is not so great as I had previously estimated ... If in our Kitty Hawk calculations we had used a coefficient of .0033 instead of .005 the apparent advantage of our surface over the plane as per the Duchemin formula would have been much greater. I see no good reason for using a greater coefficient than .0033."

<u>October 16, 1901</u>

"It would appear that Lilenthal is very much nearer the truth then we have heretofore been disposed to think."

<u>November 2, 1901</u>

"Lilienthal is a little obscure at times but, once understood, there is reason in nearly all he writes."

<u>December 1, 1902</u>

"The Lilienthal table has risen very much in my estimation since we began our present series of experiments for determining lift .... for a surface as near as possible like that described in his book the table is probably as near correct as it is possible to make it with the methods he used."

Thus the Wrights concluded that Lilienthal's data were correct and that the cause of their low prediction of the lift force was the incorrectly high value of Smeaton's coefficient. They never measured the correct value directly, but deduced it from their wind tunnel tests for an airfoil and their small number of measurements for a full-scale wing. Their reasoning, experimental work and results are all truly remarkable. They are especially impressive when one realizes that this effort was motivated entirely by the practical need to obtain information necessary to the successful design of their aircraft. This is a very early example of a process which is now so common that it is taken for granted. The demands of an engineering program may pose a question which can be satisfactorily answered only by fundamental scientific work completed outside the main thrust of the engineering effort. It was one of the great strengths of the Wrights that they were able to identify, formulate and solve crucial basic problems. In contrast, their contemporaries trying to build flying machines were able to progress only with crude trial-and-error methods of traditional 19th century engineering and invention. With their philosophy and style the Wright Brothers were solidly in the 20th century, far ahead of their contemporaries in aviation. That is a major reason for their rapid and certain progress to manned flight.

3. FUNDAMENTAL NOTIONS OF STABILITY

Nothing related to the Wright Brothers has created more confusion, controversy, discussion and at times vitriolic argument than questions of equilibrium, stability and control.

There is fairly general agreement that the Wrights' experience with bicycles taught them the virtue of control. The bicycle is unstable without active control by the rider. Thus the Wrights were not deterred by the possibility of an unstable vehicle which could nevertheless be successfully operated with practice, providing the means existed for proper control. It is also clear that control was always a central issue during development of their aircraft.*

What is by no means evident is the extent to which the Wrights inadvertently produced unstable aircraft. They certainly refused to follow their contemporaries who were preoccupied with the goal of inventing an intrinsically or automatically stable airplane. On the other hand, it is not necessary that an airplane be unstable to be controllable.

The Wrights were first to place the smaller horizontal surface forward - the canard configuration. They knew very well the history of the aft horizontal tail. In particular, they were aware that, as perceived by Cayley in 1799 and shown by Pénaud in 1872, an aircraft with an aft tail can be made longitudinally stable. Moreover, early in their program, in 1899 with the kite, and in 1900 with the man-carrying

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*It is a remarkable consequence of progress that some of the most advanced aircraft designs are based on unstable configurations, stabilized with automatic flight control systems. These are called "control-configured vehicles". The Wright Brothers deserve recognition as the first proponents of this "modern" approach to design. In a further twist of fate, these control-configured vehicles are plagued by many of problems discovered by the Wrights!

kite/glider, they experimented successfully with an aft tail. They knew that the configuration could easily be made stable. There is no doubt that they chose the canard because of fear, first expressed by Wilbur, that the aft tail carried with it an intrinsic danger. What worried them was the possible inability to recover from a stall, loss of lift induced by a vertical gust, or by the pilot upon raising the nose too far. That had been the cause of Lilienthal's death in 1896.

At least twice during the tests in 1901, Wilbur found himself in a stalled condition. By manipulating the canard he was able to get the nose down and the aircraft mushed to the ground without serious damage. He was therefore convinced that his reasoning was correct. A certain sense of security was given the pilot because he was able to see the actions of the control surface which also provided a visual reference relative to the ground.

Thus the choice of the canard configuration, the most distinctive feature of the Wright aircraft, was not based on sound technical grounds of stability. It was rather a matter of control in pitch, especially under extreme conditions. In fact, <u>the Wrights did not understand stability in the precise sense that we do now.</u> The reason is fundamental: nowhere in their work did they consider explicitly the balance of moments.* They shared that ignorance with all others trying

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*We must hedge a bit. The right wing of the 1903 'Flyer' was about four inches longer than the left, to compensate the weight of the engine, which was mounted to the right of the pilot. This is clear evidence of careful design, and an indication that the Wrights understood some of the need to balance moments as well as forces.

They shared that ignorance with all others trying to build aircraft at that time. So strictly, whether their aircraft were stable or unstable was an accidental matter. Often, changes in a design were made which would change the stability, and not always favorably. But the motivation was always the desire to affect some observable characteristic, such as undulations in pitch. From this point of view, the question of the Wrights′ intentions to design an unstable airplane is pointless.

For our later discussion of the wind tunnel data it will be helpful to understand the ideas of equilibrium and stability. For an aircraft to maintain straight motion, there must be no net force or moment acting. For horizontal flight, the vertical lift must exactly compensate the weight and the thrust of the propulsion system is just sufficient to overcome the drag. The symmetry of the aircraft guarantees that there shall be no net side force.

In order that there be no net moment tending to rotate the aircraft, the moments about three axes must separately vanish: the pitch, roll and yaw moments must all vanish for equilibrium. Much extra work is saved in practice by using coefficients rather than the moments themselves. A moment coefficient is obtained by dividing the moment by the dynamic pressure; the wing area; and a length, either the wing chord for the pitching moment or the wing span for the roll and yaw moments. The moment coefficients are given the symbols C_l, C_m, and C_n for roll, pitch and yaw respectively, as shown in Figure 3.

To ensure equilibrium or trim, the moment coefficients must vanish, $C_l=C_m=C_n=0$, a static condition. Whether or not the equilibrium state is <u>stable</u> depends on the changes of the aerodynamic moments when small disturbances are applied to the aircraft. Consider an aircraft in steady horizontal flight. Suppose that a vertical gust causes an increase in the angle of incidence between the flow and the aircraft. The initial equilibrium state may be restored if the increased incidence generates a pitching moment causing the nose to pitch down so as to reduce the angle of incidence to its initial value. By convention, a pitching moment tending to rotate the nose down, is defined to be negative. The preceding reasoning shows that for stability of equilibrium, the pitching moment must <u>decrease</u> when the lift <u>increases</u>. This behavior is sketched in the upper portion of Figure 4. The lift is plotted versus the pitching moment, with negative pitching moments to the right of the vertical axis*. For stable equilibrium the pitching moment curve, shown dashed in the sketch, must slope from the lower left to upper right and intersect the lift axis; at that point, the pitching moment is zero and small displacements along the curve are accompanied by changes of the pitching moment tending to restore the equilibrium state.

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*This convention is historical and orginated with early plots of wind tunnel data prepared in Great Britain. With this convention, the moment curves for stable aircraft fall to the right of the diagram and three plots - the drag polar, the lift curve and the moment curve - could be placed side-by-side on one sheet of paper. Theorists, on the other hand, often do not follow this convention!

The solid curve labeled "unstable" also passes through the equilibrium point, but small displacements cause changes of pitching moment which act to increase the displacement. It has been drawn to pass through a point labeled -.08, which we shall see later is the value of the pitching moment for zero lift of the 1903 ′Flyer.′ The original ′Flyer′ was very unstable in pitch. Note that a stable pitching moment curve can obviously be drawn through that point as well, but it passes through an equilibrium point (zero moment) requiring negative lift!

We can apply similar reasoning to motions in yaw, with the result sketched in the middle of Figure 4. If the nose of the aircraft is disturbed to the left of the path, the wind strikes the right side and the aircraft is slipping to the right; this is by definition a positive angle of sideslip. For directional stability, a positive (nose to the right) yaw moment must be generated, causing the nose to swing to the right into the wind. Hence the curve of yaw moment versus angle of sideslip must slope up to the right for stability. Directional stability is provided mainly by the vertical tail; the 1903 ′Flyer′ had acceptable, though not large, directional stability.

Finally we consider stability in roll, commonly called ′dihedral effect′. The main idea is that if a wing drops, a rolling moment will eventually be generated to restore the wings level. If, for example, the right wing drops, gravity causes the aircraft to fall to the right, producing a positive angle of sideslip. This motion must then create a negative rolling moment lifting the right wing. If the dihedral effect is positive, the curve of roll moment versus angle of sideslip must therefore slope downward to the right as sketched in the lower portion of Figure 4. Positive or upward dihedral angle of the wings produces positive dihedral effect. Thus, the opposite condition, negative dihedral effect, is sometimes called "anhedral" effect. This was used by the Wrights in their 1903 ´Flyer´.

To summarize, flight in stable equilibrium requires that six conditions be satisfied. For equilibrium, the three moments about the pitch, roll and yaw axes must vanish. For the equilibrium to be stable, changes of the moments produced by small deviations from the equilibrium state must act to restore the initial state. Application of this requirement has shown what slopes the moment curves must have for a stable aircraft.

In this general context we have treated equally the rotational motions about the three axes. Motions in pitch hold a special position, however, owing to fundamental characteristics of the usual aircraft having a longitudinal plane of symmetry. In steady level flight, the plane of symmetry is vertical and contains both the direction of flight and of gravity. The pitch axis is perpendicular to the plane of symmetry and rotations in pitch directly affect the vertical motion. A fundamental and general property of the pitch stability of aircraft must be emphasized. It is always true that moving the center of gravity forward will make an airplane more stable, for the following reason. When an airplane is in flight, application of an aerodynamic moment whether by action of the controls or due to an atmospheric disturbance, causes rotation about an axis passing through the center of gravity. Consider the case of a vertical gust which causes the angle of incidence to increase, so the lift is increased. Imagine that the center of gravity is very far forward, ahead of all lifting surfaces. Then, clearly, an increase of the lift forces on the wing and tail produce a rotation forcing the nose down, tending to decrease the angle of incidence. This is a stable response. Similarly, if the center of gravity is aft of all lifting surfaces, an increase of angle of incidence will be further encouraged, the change of lift forces causing the airplane to pitch up. This is an unstable reaction. It is reasonable to expect that somewhere between the unrealistically extreme locations there should be a position of the center of gravity for which the aerodynamic forces generate no net pitching moment in response to a disturbance of the angle of incidence. That location of the center of gravity is called the aerodynamic center or neutral point (N.P.) - every airplane has one. For a conventional airplane, the neutral point is somewhere on the wing chord, perhaps 30% - 40% aft of the leading edge. For a canard configuration the neutral point is much closer to the leading edge, and often lies ahead of the wing.

4. Longitudinal Stability of Aft Tail And Canard Configurations

In his classic paper describing his rubber-powered model airplane (Reference 8) Pénaud gave the first detailed analysis of longitudinal or pitch stability. It was not a general discussion; the main purpose had been to show how an aft tail can stabilize pitch motions. The limited scope seems subsequently to have helped create some misunderstanding. For example, it has often not been appreciated that just as a configuration with aft tail is not necessarily stable, so also a canard configuration (which Pénaud did not consider) may be stable or unstable. A correct theory of the stability of all cases did not appear until 1903 in the seminal paper by Bryan and Williams (Reference 9).

A wing alone can be made stable, but only if particular care is taken to use a proper airfoil shape having a reflexed camber line. This seems to have been realized first by Turnbull in 1906 (Reference 10). However, a flying wing brings its own problems and we need consider here only the more common case of a main wing and a smaller horizontal surface for stabilization and control. Four cases are possible: the smaller surface is either forward or aft of the wing, and each of those configuration may be stable or unstable.

The four are shown in Figure 5, with labels citing the best known examples of each; neutral points are labeled N.P. The lengths of the arrows in Figure 5 represent the relative loads per unit area or lift coefficient; C_L, when the configuration is trimmed for equilibrium in pitch. This shows the most important distinction between stable and unstable configurations. Whatever the relative sizes of the surfaces, the forward surface carries more load per unit area when the configuration is stable: the value of its lift coefficient is greater than that for the aft surface. As a result, if the angle of incidence is increased, the forward surface will usually stall first. This means that for a conventional stable aircraft with aft tail (Figure 5-1), the wing stalls first and may lose lift suddenly, but the aft tail continues to be effective and can be used to control pitch motions. In particular, the tail can be used to generate a nose-down moment, causing the wing to recover its lift. When the lifting forward surface of a stable canard stalls (Figure 5-2), the nose drops, but while the canard is stalled, precise pitch control is not possible.

An unstable aircraft having an aft tail (Figure 5-3), can be extremely difficult, if not fatally dangerous for man to fly, although soaring birds often fly in this condition. The most critical condition again arises with the behavior at high angles of incidence. Now the aft tail may stall before the wing, control is lost, and the wing stalls soon after. The possibility of operating such configurations successfully, and thereby gaining their advantage of increase efficiency, can be realized with the use of automatic controls. This is a subject of growing interest and application in modern aircraft design.

And so we arrive at the final case, (Figure 5-4), the unstable canard used by the Wright Brothers (and rarely since!) If the angle of attack is sufficiently high, the aft surface, now the main lifting surface, may stall first. While this appears to be extremely serious, the saving grace is that, unlike the previous case, control in not lost. And that is probably why the Wrights were successful with their unstable gliders - they always had control. If the wing has large camber, as with the Wrights' 1903 airfoil, the canard must carry additional lift to balance the large diving pitching moment due to the wing. As a result, the canard may stall first as the angle of attack of the aircraft is increased. That seems to have been the case for the 1903 'Flyer' as we shall show later.

For our wind tunnel data we estimate that the neutral point of the the 1903 Wright Flyer was about 10% of chord aft of the leading edge. The center of gravity was 30% aft of the leading edge, so the airplane was severely unstable. The difference of those two numbers, -20% or -.20 is called the static margin. For current aircraft with automatic control, the greatest negative static margin which is acceptable is about - 5%.

It follows from the discussion of stability and the neutral point that the slope of the curve lift coefficient versus moment coefficient (or simply lift versus pitching moment) depends on the location of the moment reference point, the position of the center of gravity. If the center of gravity is moved aft from a stable location, the slope tends to be less upward to the right, becoming more upward to the left. The curve must pass through the value of the residual pitching moment at zero lift, so the moment curves become skewed as shown in Figure 6. Here we have used the data taken with the 1/6 scale model discussed in the following section. The position of the center of gravity for which the curve is vertical is the neutral point; for these data, the neutral point is at approximately 0.10 times the wing chord c, or 10% of the chord.

5. Vortex Lattice Calculation of Aerodynamics

As a part of the AIAA Wright Flyer Project, two members of the Aerodynamics Committee have used modern computational techniques to calculate some of the major aerodynamic characteristics of the aircraft. Using two different vortex lattice computer programs, James Howford and Stephen Dwyer of the Douglas Aircraft Company have calculated load distributions, lift and pitching moment for the Flyer. We believe that these are the first such analyses of the aircraft and in fact may be the first applications of vortex lattice theory to a biplane!

The main idea of vortex lattice theory is that the aerodynamic influences of an object in a flow can be calculated by replacing that object by a distribution of vorticity over its surface. Vorticity is an elementary form of fluid motion which can be visualized as a collection of microscopic vortices or whorls - little tornadoes side-by-side. Figure 7 shows how the airplane is treated for this purpose. The wings, canard and vertical tail are approximated as flat surfaces having zero thickness, not a bad assumption for the 1903 'Flyer'. For these calculations the surfaces have been divided into three hundred panels, over each of which the vorticity is locally constant. The procedure requires solving 300 equations for the 300 values of vorticity or loading on the panels. No account is taken of the struts, truss wires and other structure external to the load-carrying surfaces. In the vortex lattice method the flow is assumed to be inviscid so the friction drag is zero. The drag due to lift, the induced drag, can be calculated but is not included here.

Examples of Howford's load distributions are given in Figure 8. The loading per foot of span on the lower wing is plotted for several conditions. Figures 8(a)-(c) show the influence of canard deflection. In part (a) the load distribution has the nearly elliptical form expected for changes of incidence for the wing alone. Deflection of the canard (nose up) produces downwash behind the canard and upwash in the region outside its tips. This produces a negative loading in the central portion of the wing, and a slight increase in the outboard regions, part (b). The net loading on the wing for changes of both canard and wing incidence is shown in part (c).

In Figures 8(d) and 8(e), the incremental loadings on the wing due to pitch and yaw rates are illustrated. The wake of the canard has a large influence in pitch, and relatively less in roll.

Not shown here, but evident in the results of the vortex lattice calculations, is the significant upstream influence of the wing. The spanwise loading on the wing produces a strong upwash field decaying within several wing chord lengths.

Because the canard is located within the upwash field, this aggravates the contribution of the canard to pitch instability by an additional 25 to 30 per cent.

These results show directly the obvious fact that the flow induced by the canard may have substantial effects on the lift generated by the wing and vice versa. This feature cannot be ignored in analysis of the aerodynamics of the 'Flyer'. Suitable integration of results such as these will give the total lift and moment for the aircraft. The good accuracy of the calculations will become apparent upon comparison with data taken in wind tunnel tests.

6. Results and Interpretation of Wind Tunnel Tests

We have carried out two series of wind tunnel tests within the A.I.A.A. Wright Flyer Project. The first used a 1/6 scale model shown in Figure 9. They were carried out in the GALCIT ten foot tunnel at the California Institute of Technology (Reference 11). Because one of the main intentions of the tests was to obtain data for the effectiveness of wing warping, the model was built of wood and fabric, with steel truss wires, very similar to the original aircraft. As a result, the structure was relatively fragile and suffered considerable damage during the test program. Some of the results seem to be biased because of distortions of the wing surfaces.

The second series of tests used the stainless steel model, 1/8 scale, shown in Figure 10 (Reference 12). Extensive tests were carried out, including changes of configuration to investigate possible modifications for the full-scale flying reproduction mentioned earlier. An advantage of the steel model is that data can be taken at higher speeds, or Reynolds numbers. The Reynolds number for the tests varied from 50 to 90 per cent of the value in full scale flight. In this range the aerodynamic properties suffer only small changes.

Figure 11 is a sketch of the profile of the aircraft showing the definition of several quantities which are important in presenting the data. We have chosen the reference location of the center of gravity to be 30% aft of the leading edge of the lower wing and 30% of chord above the lower wing. This choice is based on estimates by Professor Hooven of Dartmouth College and by Mr. Charles McPhail of the AIAA Wright Flyer Project. The bottom of the skid rail is the horizontal reference. A line drawn through the centers of the leading edge and the aft spar is parallel to the skid line; this defines the angle of zero incidence of the upstream flow. The same reference line defines the zero angle of canard deflection.

6.1 Lift and Drag Aerodynamics

Here we shall discuss only a portion of the data, to illustrate some comparisons between experiment and theory, and to cover some of the results used later in calculations of the stability, control and dynamics of the airplane. Figure 12 shows two of the basic characteristics of an airplane, the drag polar, lift coefficient versus drag coefficient; and the lift curve, lift coefficient versus angle of attack. Because the steel model has larger structural members for strength at the higher test speeds, the drag is larger than that for the 1/6 scale model (called covered model) at the lower lift coefficients. The horizontal cross-hatched line is drawn at the value of lift coefficient we estimate to be that for cruising flight of the original Flyer. The agreement of data for the drag of the two models at this value of lift coefficient must be regarded as fortuitous: data for drag are often suspect, and especially for these models the results maybe sensitive to the value of the Reynolds number.

The lift curve slope obtained with the steel model is very closely matched by the calculations based on vortex lattice theory, showing an angle of incidence of about one degree at cruise. This suggests again the understanding of aerodynamics possessed by the Wright Brothers: it appears that the geometrical setting of the wing, with respect to the skid rail, was very closely that required for cruise flight. The lift curve for the covered model has closely the same slope as the other two results but is displaced by roughly four degrees to higher angles of attack. This seems to be due to an average reduction of the camber of the airfoil due to distortion of the structure. In any case, both sets of data show that the cruise lift coefficient is well below the value for stall of the aircraft, further evidence of careful design by the Wrights.

6.2 Pitching Moment Aerodynamics

A summary of our present understanding of the pitching moment of the 1903 Flyer is given in Figure 13. The best data, those taken with the steel model, are displayed as open symbols; results are shown for three canard settings, 0 degrees and ±10 degrees. It appears that a deflection of about +6 degrees (nose up) is required for a trim condition having zero pitching moment at the cruise lift coefficient of 0.62. But according to our earlier discussion of Figure 4, this is an unstable condition because the slope of the curve lift coefficient versus moment coefficient is downward to the right.

The data taken with the 1/6 scale covered model are plotted as the crosses. These show a smaller value of pitch down pitching moment at zero lift. Correspondingly, the elevator deflection for trim is nose down, producing a pitch-down moment on the airplane. The smaller pitching moment at zero lift is consistent with the smaller angle of incidence for zero lift shown by the data in Figure 12. Both deficiencies may be explained by somewhat less camber or a small amount of symmetrical twist (trailing edge up) of the wings on the covered model. It appears that the second may be the more likely explanation - unless the data for the steel model and the result of the vortex theory are both in error!

Whatever the case, it is best not to try to "correct" the data, a practice universally understood now, but less well-recogized in the Wrights' time. In a letter to Chanute, Wilbur offered the following astute observation concerning Langley's treatment of some of his own data for lift on a flat plate: "If he had followed his observations, his line would probably have been nearer the truth. I have myself sometimes found it difficult to let the lines run where they will, instead of running them where I think they ought to go. My conclusion is that it is safest to follow the observations exactly, and let others do their own correcting if they wish." (Reference 1, p. 171). We follow Wilbur's dictum and present both sets of our wind-tunnel data.

The unstable pitching characteristic of the 1903 Flyer is arguably its worst feature, although as we shall see, the lateral characteristics are also poor. The large negative static margin (-20%) meant that the airplane was barely controllable. Three factors made the flights on December 17 possible: the low speed, high damping of the pitching motions, and most importantly the Wrights' flying skills. During their development work leading to the 1905 airplane, the first practical airplane, the Brothers made two important changes: they increased the area of the canard, and they added weight, as much as 150 pounds, to the forward canard post, to bring the center of gravity forward (reference 13).

Those improvements were made to ease the difficulties they encountered controlling undulations in pitch, a dynamical consequence of the static instability we have been examining. In fact, the most significant cause of the unstable pitch characteristic is the large negative pitching moment at zero lift (Figure 12). Referring to Figure 4, we see that in order to be able to trim an aircraft for a condition of stable equilibrium, it is necessary that the pitching moment at zero lift be <u>positive</u>.

The large negative pitching moment at zero lift of the 1903 'Flyer' is due almost entirely to the airfoil. A highly cambered airfoil must operate at a relatively large negative angle of incidence to produce zero lift. At that condition the pressure distribution is such that a large negative (nose-down) pitching moment is generated. This is easily demonstrated qualitatively - hold a curved plate in an airstream. It is possible that the Wrights were aware of this behavior, but it is more likely that they were not. Nowhere do they discuss the pitching moment characteristics of airfoils. We have already remarked that they were apparently unaware of the necessity for using the equation for moments to obtain a thorough and correct understanding of stability.

So the Wrights followed Lilienthal and used thin, highly cambered airfoils resembling the cross-sections of birds' wings. They were misled to believe that airfoils of that sort produced the highest ratio of lift/drag. There is in fact much truth in this conclusion if data are taken for small wings at the low speeds the Wrights used in their wind tunnel tests. Thicker airfoils having less camber are superior for full scale aircraft. However, it is the large negative pitching moment of the Wrights' airfoil that is the main issue. Simply by reducing the camber, they could have achieved enormous improvement in the longitudinal flying characteristics of their aircraft. In their later aircraft they apparently reduced the camber, but not as much as they could have.

6.3 Directional Aerodynamics

The data for lateral and directional characteristics of the two models, plotted in Figures 14 and 15 seem to agree acceptably well. The sideforce generated in sideslip, Figures 14a and 15a, is relatively small because there is practically no side area other than the vertical tail. The slope of the curve C_n versus β is small but positive as it should be for directional stability (Figures 14b and 15b). According to the shift of the curves - i. e. the change of yaw moment with rudder deflection, δ_R - the rudder had plenty of control effectiveness. A rudder deflection of ten degrees gives zero yaw moment for a trim angle of sideslip equal to eight degrees. That means that in steady flight, 0.8 degrees of sideslip can be maintained for each degree of rudder deflection. This should be compared with a pure vertical tail alone for which one degree of rotation would trim at exactly one degree of sideslip.

6.4 Lateral Aerodynamics: Anhedral

One of the distinctive features of the 1903 ´Flyer´ is that the wings are rigged for anhedral - the tips are "arched" as the Wrights called it, about eleven inches below the centerline. This produces a positive variation of roll moment with sideslip which, according to our remarks in connection with Figure 4c, is an unstable response. Suppose that in steady level flight the right wing tip drops. Gravity causes the airplane to slip to the right, giving a positive angle of sideslip. It is evident that with anhedral, the cross wind tends to strike the upper surface of the lowered wing, forcing it to fall further. This is an unstable response.

Thus we see in both Figures 14c and 15c that the slope of the data for roll moment versus sideslip is positive as expected. The slope is less for the data taken with the 1/6 scale covered model, a result which may be at least partly explained by symmetric twist which would tend to reduce the anhedral of the outer portions of the wing. Both curves are biased so that there is a non-zero (negative) value of roll moment even with no sideslip. This is due to the fact that the right wing has slightly larger span than the left, approximately four inches for the full-scale Flyer. The Wrights built in this small asymmetry to compensate the weight of the engine which was heavier than the pilot located on the other side of center.

The use of dihedral was invented by Cayley sometime after 1800. Its purpose is to provide stability in roll as described earlier. From the beginning of their work, the Wrights chose not to use dihedral. Writing to Chanute in February 1902, Wilbur refers to a letter by a third party,

> "He seems surprised that our machine had a safe degree of lateral equilibrium without using the dihedral angle. He has not noticed that gliding experimenters are unanimous in discarding that method of obtaining lateral stability in natural wind experiments" (Reference 1, p. 217).

While others, like Lilienthal, were shifting their weight to maintain lateral equilibrium, the Wrights were using wing warping, which gave them a great deal more control.

In 1900 and 1901 the Wrights' gliders had anhedral, to discourage the natural tendency for the aircraft to maintain equilibrium, and to allow more effective use of the warp control. Their first glider in 1902 was rigged so the wings were straight (Reference 1, p. 322). But early in their 1902 flying season, the Wrights again installed anhedral. The reason was a problem they encountered because they were gliding close to the surface of sloping ground. Orville wrote in this diary in September 1902:

> "After altering the truss wires so as to give an arch to the surfaces, making the ends four inches lower than the center, and the angle at the tips greater than that at the center, we took the machine out, ready for experiment ... We found that the trouble experienced heretofore with a crosswind turning up the wing it first struck had been overcome and the trials would seem to indicate that with an arch to the surfaces laterally, the opposite effect was attained." (Reference 1, p. 258).

What they disliked was the obvious consequence of dihedral: if the airplane is exposed, say to a crosswind from the right (which is the same as positive sideslip), the roll moment which is generated by positive dihedral lifts the right wing, as the wind "catches" the undersurface. When the aircraft has low directional stability - as the case was for their glider - there is only a weak tendency for the nose to turn into the wind. The net effect for their early gliders was that the left wing tip was driven towards the ground. In an attempt to counteract this motion, Wilbur had operated the canard to raise the nose and the glider stalled, ending in a crash landing. That is the "trouble experienced" mentioned in the above quotation, and the reason why the Wrights favored anhedral which produces the opposite effect: in response to a gust the airplane automatically rolls away from the hill.

That was fine for short, nearly straight flights in gliders at the Kill Devil Hills. The powered flights in 1903 were too brief to show otherwise. But the Wrights discovered during their flight tests of 1904 and 1905 that anhedral has serious undesirable consequences, particularly in turning flight.

Suppose the right wing drops, so gravity causes the aircraft to slip to the right. If the wing has anhedral, this positive sideslip generates a rolling moment tending to lower the right wing further (the cross wind produces increased pressure on the upper surface of the right wing). That is obviously an unstable sequence of events. If, as usually is the case, the aircraft has positive directional stability, the nose will be swung into the wind, here to the right. The net result is that in a right turn, the right wing continues to drop; the aircraft changes heading to the right and what begins as a small disturbance develops into an unstable spiral.

The motion just described is an unstable form of a fundamental aircraft motion called the spiral mode. It is part of aircraft dynamical stability, a subject more complicated than the matters of static stability we have discussed so far. For example, an aircraft may be stable in roll (positive dihedral effect) but if the directional stability is sufficiently large, the spiral mode will be unstable. Thus, although the aircraft is statically <u>stable</u> in the sense shown in Figure 4, it is dynamically unstable. That is, in fact, commonly true of full-scale aircraft.

We shall discuss the dynamics of the 1903 'Flyer' in the following section using modern techniques of analysis. The Wrights learned the hard way, by flight tests, that anhedral aggravated the spiral instability with dangerous consequences when they tried to turn the aircraft. Although we are here concerned mainly with the 1903 Flyer, it is interesting to learn what the Wrights did about anhedral in their later aircraft. In September 1904 they began practicing turns, attempting a full circle first on September 15. They succeeded on September 20. Then on September 26, Wilbur noted in his diary that Orville had been "unable to stop turning." The same entry appears on October 15, but this time the aircraft suffered serious damage. "Unable to stop turning and broke engine and skids and both screws, Chanute present." On the same day, Chanute noted in a memorandum, "Wright thinks machine arched too much and speed too great across the wind." Thus they seem to have correctly located the problem as the anhedral causing the spiral mode to be so unstable as to make controlled turning extremely difficult.

After removing the anhedral, the Wrights began flying on October 26. The first flight again ended with damage to the aircraft. Referring to this incident in a letter to Chanute on November 15, Wilbur noted "the changes made to remedy the trouble which caused Orville's misfortune gave the machine an unfamiliar feeling, and before I had gone far I ran it into the ground and damaged it again. On November 2nd we circled the field again, and repeated it on the 3rd. On the 9th we went out to celebrate Roosevelt's election by a long flight and went around four times in 5 minutes 4 seconds." Photographs* of the airplane with anhedral (August 13) and without anhedral (November 10) are reproduced here as Figures 16 and 17.

Although they were able to turn, success was intermittent. In fact, the day after he wrote to Chanute, Wilbur remarks in his diary, "Unable to stop turning." Their last flight in 1904 was on December 7 and the problem of turning was still unsolved.

The difficulties the Wrights encountered in turns were only partly due to the spiral instability. They believed later (reference 1, footnote, pp. 469-471) that the control system was a serious cause as well. In all of the flights referred to above, the wing warping and rudder deflection were interconnected as in the 1903 'Flyer.' They recognized that this restricted the control they had and finally in 1905 decided to operate the controls independently.

At the beginning of the tests in 1905 (late August) the wings were rigged with a small amount of anhedral which was later removed. Together with independent control of yaw and roll, this gave the Wrights an airplane they could turn controllably at speed and altitude. They then discovered the last problem they had to solve to have a practical airplane: stalling in a turn. Between September 28 when they first flew in 1905 with independent warp and rudder, and October 5

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*Plates 84 and 86 of Reference 1.

when they flew for 38 minutes, the Wrights learned how to recover from a stall. Wilbur's description in his summary of the experiments in 1905 (reference 1, pp. 519-521) is a superb statement of the problem and its solution:

> "The trouble was really due to the fact that in circling, the machine has to carry the load resulting from centrifugal force, in addition to its own weight, since the actual pressure that the air must sustain is that due to the resultant of the two forces. ...When we had discovered the real nature of the trouble, and knew that it could always be remedied by tilting the machine forward a little, so that its flying speed would be restored, we felt that we were ready to place flying machines on the market."

What a magnificent achievement! In the seven days from September 28 to October 5, 1905, the Wright Brothers solved their last serious problem and had a practical airplane. They didn't fly again until 1908, but that's a different story.

6.5 Lateral Aerodynamics: Warping effectiveness

One of the major purposes of the wind tunnel tests with the 1/6 scale covered model was to investigate the quantitative aspects of wing warping. This method of lateral control was original with the Wrights and after their first flights in 1908 it was quite widely adopted.* But within five years it had been almost entirely discarded in favor of ailerons. Hence no wind tunnel data had been taken for the performance of warping. It is an important matter of historical documentation to establish quantitatively how this method of control worked. Some of the results of the GALCIT tests are summarized in Figure 18.

The top portion of Figure 18 shows the effects of warping the wing with no rudder deflection. Data are plotted for no warp (open circles) and maximum warp (open triangles). As noted earlier in connection with Figures 14 and 15, a non-zero roll moment exists with no warp deflection because the starboard wing is longer than the port wing. The roll moment produced is slightly dependent on α, the angle of attack. However, the adverse yaw moment accompanying the warp is strongly dependent upon α. It is adverse yaw in the sense that a right turn produces a yaw moment tending to turn the nose to the left.

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*The Wrights used a Pratt truss between the upper and lower leading edges; the vertical struts carry compressive loads and diagonal wires carry loads in tension. This design provided a rigid, arched "beam" as the forward section of the biplane. The center portion of the biplane was also rigidly trussed at the aft spars. But the outboard 40 percent of the aft spars were trussed by a set of wires to permit controlled warping. When the trailing edges of one pair of tips are twisted up, the trailing edges on the opposite side twist down. Clever structural design is necessary to reduce the wings' resistance to warping so that the control forces are not too large: the aft spar is mounted loosely within each rib; rib loads are carried across the spar by spring metal caps on top and bottom; aft spar joints at the center section are hinged; and the fabric covering is cut on-the-bias to reduce the resistance to torsion. Those working on the A.I.A.A. Wright Flyer project have great respect for the Wrights' ingenious solution to this problem.

Wilbur made his fundamental discovery of adverse yaw, during his flights in 1901. He noted in his diary on August 15, "Upturned wing seems to fall behind, but at first rises." Then in a letter to Chanute on August 11, he wrote, "The last week was without very great results though we proved that our machine does not turn (i.e. circle) toward the lowest wing under all circumstances, a very unlooked for result and one which completely upsets our theories as the causes which produce the turning to right or left." These are the first observations of adverse yaw. They could only be made by someone who understood something of aerodynamics and flight mechanics but especially was trying to learn to fly and was a keen observer.

Adverse yaw arises in the following way. In order to turn, as the Wrights understood from the beginning of their work, it is necessary to generate a component of force towards the center of the turn. This is best accomplished by tilting the lift force on the wing, which is done by banking the entire aircraft. A bank is produced by applying a roll moment, generated by increasing the lift on one wing and reducing the lift on the other. When that happens, whether by wing warping or by using ailerons, the drag is increased on the wing carrying more lift and reduced on the other. The differential drag acts as a yaw moment tending to swing the nose of the aircraft in the direction opposite of that of the desired turn - hence the name adverse yaw. It inevitably accompanies any turning maneuver. Although adverse yaw is low at higher flight speeds, and can be reduced with clever design of the lateral control system, what is really required is control in yaw, and that is why a vertical control surface or rudder must be installed.

The most fundamental aspect of the Wrights' invention of the airplane was the idea of the need for control of both roll and yaw motions. It is the foundation of their basic patent submitted in 1902 and granted in 1906. Wilbur had discovered the problem of adverse yaw in 1901. Their first glider in 1902 had a fixed vertical tail which, with anhedral, gave flying characteristics which they considered to be the most difficult of all their aircraft. They quickly installed a moveable tail which of course gave them the necessary control in yaw.

Warp and rudder deflections were interconnected in the 1902 glider and in the 1903 airplane. Although the controls were later made independent, interconnection was a fortunate choice for the 1903 machine, as we shall see in the following section. The data plotted in the lower portion of Figure 18 shows how simultaneous deflection of the rudder with warping compensates for adverse yaw. The curve labelled $\delta_r = 12.5°$ crosses the axis, indicating zero yaw moment, at $\delta_r = 4°$. For the covered model (see Figure 12) this is nearly the angle of attack for the cruise condition. Thus for this speed only, this combination of warp and rudder deflection will produce a roll moment with no adverse yaw, which allows entry to a banked turn with no sideslip - i.e. a more coordinated turn.* By

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*This conclusion is not wholly correct because our discussion is oversimplified and incomplete. We have ignored the effects of the sideforce generated by rudder deflection.

disconnecting the warp and rudder controls in their 1905 airplane, and installing both controls on a single stick, the Wrights were then able to execute coordinated turns over a range of airspeeds, in a convenient fashion.

6.8 Summary of Wind Tunnel Tests of the 1903 Flyer

The results of these wind tunnel tests have greatly increased our understanding of the flying characteristics of the 1903 Flyer. It appears that the data are reasonable and agree well with predictions based on modern aerodynamic theory.

According to these data, the trimmed flight condition of the aircraft is near the optimum, being at a value of lift coefficient slightly less than that for maximum lift/drag ratio. This provided ample margin below stall of the aircraft, a primary consideration particularly in view of Lilienthal's fatal crash.

The canard gave sufficient power in pitch to control the unstable motions, and the vertical tail was adequate to control yaw. The combination of wing warp for roll control and a linked rudder to remove the associated adverse yaw provided powerful lateral control for banking the airplane and for coping with gusts. No contemporary aircraft had control even approximating that of the 1903 Flyer until after the Wrights publicly flew their improved airplane in 1908.

7. Dynamical Stability and Control

Our discussion of the wind tunnel data has verified and clarified most of the important static characteristics of the 1903 Flyer - static stability and control effectiveness. With our data, and estimates of a few quantities, we are able to describe quite accurately the dynamics of the airplane, in quantitative terms not available to the Wrights.

Because the 1903 'Flyer' logged a total flight time of only 1 minute 58 seconds, the flight characteristics and handling qualities of the airplane were never fully tested. That it was flyable was of course demonstrated - under severely gusty conditions. In this section we try to convey some idea of how the airplane probably behaved, by examining two elementary transient motions of pitching and turning.

First a few general remarks on unsteady or dynamical motions of aircraft. We assume that the airplane has a plane of symmetry containing the longitudinal and vertical axes.* It is then a general theoretical consequence of the equations of motion that if the disturbances away from steady flight are not too large, then the unsteady motions can be split into two parts: purely longitudinal motions involve changes of the forward speed, pitch attitude, and vertical speed, or angle of attack. The lateral motions are out of the plane of symmetry, comprising roll, yaw and sideways translational motion or sideslip.

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*The assumption is only slightly strained because of the deliberate asymmetry mentioned earlier. This has very small effects on the results.

The practical consequence of this general splitting or uncoupling of the motions is that, for example, movement of the pitch control (elevator or canard), or a purely vertical gust, will not generate lateral motions out of the plane of symmetry, and conversely. This is the reason why we can rigorously treat the pitch dynamics separately from the lateral dynamics. It is a good approximation to actual motions.

7.1 Dynamics of Pitching Motions

We have already established that the Wright Flyer was statically unstable in pitch. That means that if it is even slightly disturbed from a condition of steady flight, there is no tendency to restore the initial steady motion. Thus if the pilot does nothing, the airplane will exhibit a divergent nose-up or nose-down departure.

Figure 19 shows the results of a calculation. Suppose that in level cruise flight* the pilot suddenly deflects the canard nose-up one degree and immediately returns it to its previous setting. The same input can be can be imagined due to an infinitesimally short vertical gust having speed roughly 3/4 foot per second, a mild gust. This pulse input is represented in Figure 19(a). The remaining four parts of the figure clearly show the subsequent divergent motions in angle of attack, pitch (nose-up), airspeed (decreasing) and altitude (increasing). In approximately one-half second the amplitude

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*Because the airplane is unstable this condition can in reality exist only for a brief time. For calculations we can ignore that practical problem and assume that we start from the desired state of nice level flight.

of the motion doubles. Thus, if the angle of pitch is, say five degrees at some time after the canard has been pulsed, then the pitch angle is already ten degrees only one-half second later.

The airplane alone is obviously very unstable both statically and dynamically. However, it can be controlled by a skilled pilot - the practical consequence is that the combination of airplane plus pilot is a dynamically stable system. It is analogous to the manner in which a statically unstable bicycle with a trained rider is stabilized. So far as reaction time is concerned, stabilizing the 1903 Flyer is roughly equivalent to balancing a yardstick vertically on one′s finger!

Practice is required - the Wrights had lots of that. Here, to demonstrate the idea, we assume that in response to a disturbance the pilot tries to maintain level flight with a simple strategy. The pilot can see the horizon and he knows where some horizontal reference line on the canard should lie with respect to the horizon in level flight. Then to restore level flight, the pilot deflects the canard by an amount which is proportional to the error between the actual location of the reference line and its desired position in level flight. Thus, the canard deflection is proportional to the pitch error; the constant of proportionality is called the pilot′s "gain".

The airplane and pilot, with the assumed proportional control, constitute a feedback system. We interpret its behavior in a root locus diagram, sketched in Figure 20. It is not appropriate here to discuss the theory of this diagram; we shall only explain briefly its meaning and the implications of the results.

At the top of Figure 20, the feedback system comprising the airframe plus pilot is represented as a block diagram. The equation for the transfer function labelled "open loop" is used to calculate the response of pitch angle, θ ,to a sinusoidal variation of canard deflection with maximum excursion + δ_e (nose-up) and - δ_e (nose-down). With suitable operations, this formula can be extended to compute the response in pitch to any variation of canard deflection; that is how the results shown in Figure 19 were found. These results follow from the complete linearized equations for longitudinal motions; their derivations will not be described here. Reference 14 contains a thorough coverage of the theory. The paper by Professor Hooven (Reference 17) shows how to compute the real-time response using a digital computer as a simulator.

The denominator of the open loop response is shown as the product of three factors, one labeled "phugoid" and two together identified as "short period." It is helpful in explaining Figure 20 to remark briefly on the origin of these terms.

We have already noted that under quite general conditions, the longitudinal dynamics can rigorously be treated separately from lateral motions. For most aircraft, there are two fundamental modes of longitudinal motion, called the short period and phugoid oscillations. The phugoid was discovered, analyzed, and named in a remarkable work by F. W. Lanchester in the mid 1890's (Reference 15) based on his observations of the flights of model aircraft.* This is a relatively slow undulating motion whose behavior is dominated by the interchange of kinetic energy of forward motion and potential energy of vertical motion. The angle of incidence remains nearly constant while the pitch angle changes, being horizontal near the maxima and minima of the undulations. It is the phugoid mode which causes difficulties in trimming aircraft when changes of pitch attitude are made.

The second fundamental mode of motion, the short period oscillation, normally has frequency much higher than that of the phugoid mode. Now the aircraft behaves as an oscillator or weathervane in pitch, the mass being the moment of inertia in pitch and the "spring" being proportional to the static stability in pitch, the static margin. The forward speed remains nearly constant and the nose bobs up and down with the angle of incidence approximately equal to the angle of pitch. Because the tail (or canard) also moves up and down with the periodic motions, there is considerable damping of the motion. It is the short period oscillation which usually tends to be most easily excited by sharp gusts and turbulence.

Now back to the Wright 1903 Flyer. In the context of aircraft dynamics, this is distinctly not a conventional machine, which makes its study particularly interesting. First we find that, because the airplane is statically unstable in

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*Lanchester chose the term phugoid based on Latin and Greek roots meaning "to fly". He mistakenly selected roots meaning to fly in the sense of to flee - as in ´fugitive´. Lanchester´s aerodynamics was much superior to his etymology.

pitch, the usual short period oscillation doesn't exist. It degenerates to two simpler fundamental motions, one of which decays with time and the other of which diverges following a disturbance. The latter is responsible for the behavior shown in Figure 19. The phugoid is lightly damped, as normally true, and has a period of about five seconds. A typical general aviation aircraft will have a period of say 30-40 seconds for the phugoid and less than one second for the short period oscillation. Hence what we call here the "phugoid" is really something between the conventional phugoid and short period oscillation.

The coordinates in Figure 20 are the angular frequency ω in radians plotted vertically, and decay or growth constant, $1/T$ plotted horizontally. The period of motion is $2\pi/\omega$ and the amplitude of motion varies as $\exp(t/T)$. Thus, if $1/T$ is negative - i.e. lies on the left side of the diagram, the motion decays, proportional to $\exp(-t/T)$ and after $t=T$ seconds the amplitude is reduced by a factor of about 0.37. The crosses in Figure 20 denote the roots of the denominator of the formula for θ/δ_e and represent the natural motions when the pilot does nothing - the canard surface remains fixed. These points are labeled ω_p, denoting phugoid, and $1/Tsp_1$, $1/Tsp_2$ denoting the degenerate short period. Note as remarked above that one of the latter two lies to the right of the vertical axis, representing a divergent motion, and one lies to the left.

Now suppose the pilot acts as described earlier, and continually deflects the canard in opposition to the perceived pitch deviation to maintain a desired pitch attitude - the "loop is closed." The fundamental motions of the complete system, aircraft plus pilot, must clearly be different from those for the "open loop," or aircraft alone. A different formula for θ/δ_e is found and the roots of its denominator are different from those plotted as the crosses. In particular, the values of the roots depend on the gain, K_p, of the pilot - i.e. how much he deflects the canard for a unit perceived error. As K_p is changed, the each root traces a locus starting at the open loop cross, and hence the name "root locus diagram."

The filled squares in Figure 20 represent the roots when $K_p = 4$, meaning that the pilot deflects the canard by 4 degrees for every degree of error he sees. Both roots on the horizontal axis now represent stable motions which always decay. The root representing the oscillation has now moved to higher frequency and is still lightly damped. This frequency, roughly 0.9 Hertz, the period being about 1.1 seconds, is in the range for which pilot-induced oscillations will occur. They were likely a problem for the 1903 Flyer, as shown by photographs in which the canard is deflected fully up or down.

Figure 21 is a sketch of the time response for a one degree pulse of the canard, corresponding to the case shown in Figure 19, but now the pilot exercises proportional control ($K_p = 4$). Both the horizontal speed and the height are successfully maintained constant, but the nose bobs up and down at about 1.1 cycles per second; after about two cycles the amplitude is reduced by half. Thus we have found that even though the airplane alone is seriously unstable in pitch, it is controllable by a reasonably skilled pilot.

This behavior more closely resembles the short period motion than it does the phugoid. As we noted above, the lightly damped oscillation of the airplane alone really cannot be called a phugoid and we have here further support for this view. The origin of this unusual behavior is of course the unorthodox combination of aerodynamic characteristics, including the unstable configuration, and its inertial properties. Having a wingspan of 40 feet, the 1903 Flyer was quite large, but its wing loading was only 1.5 pounds per square foot, which places it in the class we now call ultralight aircraft. One important consequence of the low wing loading is that the mass of air which must be moved in accelerated motions - the virtual mass and virtual inertia - is a significant fraction of the mass of the airplane; here about 20%! This has been accounted for in the results shown, and explains part of the peculiar behavior.

Approximate values of the virtual inertia coefficient have been used in the results given here, while its calculation is being refined for a biplane cell having finite aspect ratio. However there is no doubt that the oscillatory motion shown in Figure 21 is real. Films of the Wrights flying their improved aircraft in 1909 show clearly exactly this kind of continously oscillating pitch control at about the same frequency.

7.2 Dynamics of Lateral Motions

The Wright Brothers were the first to understand the correct method for turning an airplane. Lilienthal and other glider pilots he inspired were largely content to maintain lateral equilibrium by building wings with dihedral, and shift their weight as required during flight. Contemporary experimenters with early powered aircraft, such as Voisin in France, tried to skid around turns by deflecting the rudder. Only the Wrights realized that good roll control is essential for turn entries and exits. They devoted a large part of their flight test program to the problem of turning; only after they were satisfied with their solution did they set out to sell their invention. We have discussed the main features of their system for control of roll and yaw of the 1903 Flyer. Now let us see how it actually performed in flight.

According to discussion in the preceding section, one can treat the lateral motions independently of pitching motions. Before analyzing the particular behavior of the Flyer, it is helpful to consider some elementary characteristics of a turning maneuver. Imagine an airplane in steady level flight, and suppose that a means for applying a roll moment is available, by deflection of ailerons, or by wing warping. A fixed value of deflection or warp generates a constant roll moment. If a constant roll moment is suddenly applied, the airplane is first accelerated in roll, but soon settles down to a constant roll rate, so the bank angle increases linearly in time.* The rate is constant because the moment due to the distorted wings is compensated by the damping in roll, a moment opposing the movements of the large surface areas normal to themselves. Figure 22 shows this behavior for the 1903 Flyer, the lateral response for an impulsive warp deflection, two degrees of warp held for one-half second, with no rudder deflection. The unstable nature of the motion is clearly shown by the rapid divergence of roll and sideslip angles. Note that owing to adverse yaw, the heading rate is initially in the direction opposite to that desired.

Evidently, to execute a turn with a fixed bank angle, the roll moment must first be turned on and then removed. Simultaneously, the rudder must be used in such a fashion as to compensate adverse yaw and reduce the sideslip to zero. Considerable practice is required to perform smooth turns.

Analysis of the turn may be carried out using the methods described above. We require that, beginning from steady level flight, the pilot actuate the controls in such a manner as to roll the airplane into a constant angle of bank. The root locus diagram in Figure 23 has been constructed for this situation. Below the block diagram is the equation labeled open loop response, a formula for the response of roll angle to wing warp, δ_w. The crosses in the diagram again represent the

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*Note that in contrast, for a stable aircraft, fixed deflection of the elevator, which produces a constant change of the pitching moment, causes a constant change of pitch <u>angle</u> (or angle of incidence) <u>not</u> a constant pitch <u>rate</u>. This is different from roll motion because the pitching moment due to the elevator is compensated by a change in the pitching moment due to the lift of the wing. If the aircraft is unstable in pitch, as the 1903 Flyer was, the two contributions to the pitching moment act together and the pitch attitude of the airplane diverges.

roots of the denominator. One lies to the right of the vertical axis, and corresponds to the unstable spiral mode described earlier. If the wings are impulsively warped, and returned to their undistorted state, or if the airplane is exposed to a short vertical gust unsymmetrical about the centerline, a divergent spiral motion will develop, as previously explained.

Another root lies far to the left; this is labeled "roll subsidence" and arises from the heavy damping of roll motions. The third root, ω_{DR}, represents a damped oscillation, the subscript DR standing for "Dutch roll".* This is primarily an oscillation in yaw angle a mode due to the action of the vertical tail as a weathervane. This induces oscillatory motions in both roll and sideslip. Damping of the motion is provided mainly by the vertical tail and drag of the wings and struts, due to the differential airspeeds accompanying yaw rates.

These three modes - the spiral mode, the roll subsidence and the Dutch roll - are the natural lateral motions of all aircraft. In this respect, the lateral behavior of the 1903 Flyer is generically the same as conventional aircraft which normally can be characterized by the same lateral modes. However, the spiral mode is unusually unstable, the amplitude doubling in about 2.5 seconds. This rapid growth is due largely to the anhedral as we discussed earlier. Partly

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*The origin of the term "Dutch roll" is obscure. The eminent aeronautical scientist Theodore von Karman once explained that it was a contraction of the naval jargon "Dutchman's roll", alluding to the motion of round-bottomed Dutch ships in the North Sea, or of round-bottomed Dutch sailors ashore. Take your pick.

because of the low speed and partly because of the low directional stability compared with the large yaw inertia, the period of the Dutch roll oscillation is relatively long, roughly 4.8 seconds. It is not heavily damped due to the relatively small vertical tail and hence small damping in yaw.

Now consider a simple model of a turn maneuver. Suppose that the pilot wishes to obtain a bank angle equal to ten degrees, which he observes as the angle between the horizon and the canard reference line. As a control law we assume that the pilot operates the warp control by an amount proportional to the error, the difference between the desired bank angle (10 degrees) and that actually observed; the constant of proportionality is the gain, K_p. Two cases are treated: pure warp, with no deflection of the rudder; and interconnected warp/rudder. The second corresponds to the control system in the 1903 Flyer; the drawings obtained from the Smithsonian Institution imply that the rudder is deflected -2.5 degrees for each degree of warp deflection. As for the longitudinal motions, the locus of roots can be calculated for the two cases, shown in Figure 23. For increasing gain, the roots corresponding to the spiral mode and roll subsidence move towards each other on the horizontal axis and then depart vertically, representing the formation of a heavily damped "spiral-roll" mode whose dynamics characterize the major portion of the response in roll.

More interesting is the dependence of the Dutch roll "nuisance" oscillation on the gain. For the case of pure warp, this becomes marginally damped for a reasonable value of the gain, 1.0 degrees of warp for each degree of perceived error. The time history for this motion is shown in Figure 24(a). Large oscillations of bank angle, heading rate, and sideslip make this a wallowing motion nearly impossible to control and wholly unsatisfactory for practical flying. It is mainly due to the combination of anhedral and uncompensated adverse yaw.

When the rudder deflection is linked to the warping, thereby cancelling the adverse yaw, the result is a turning maneuver which is quite acceptable. The closed loop damping is now much higher - the filled square in Figure 23 lies well to the left of the vertical axis. The much improved response in time appears in Figure 24(b). Now the bank angle tends to a constant value, albeit not equal to the desired value (10 degrees) within the time scale shown. There is a fairly large angle of sideslip, so it is a sloppy uncoordinated turn, but surely possible. Thus the interconnection of the warp and rudder is an essential feature of the 1903 Flyer.

As the Wrights discovered in 1905, satisfactory control is achieved only by warp and rudder coordination more complicated than proportional interconnection. It has often been stated, incorrectly, that the Wrights abandoned their interconnected warp and rudder. In their 1908 airplane, with the pilot sitting upright, they put both rudder and warp controls on a single stick. Lateral hand motion caused warp, while fore-and-aft motion deflected the rudder. Consequently any desired proportion of warp and rudder could be produced by operating the stick in a suitable diagonal path. Far from abandoning warp/rudder interconnection, the Wright Brothers ingeniously provided a ratio instantly adjustable according to the trim speed or angle of attack. The data discussed earlier (Figure 12) suggest the need for this flexible control.

Further evidence that the Wrights had a most advanced understanding of aircraft control appears in a short French monograph published in 1909 (reference 16). M. Pol Ravigneaux, evidently instructed by the Wrights, gave a detailed analysis of the stick movements required to accomplish various lateral motions. A few remarks taken from the discussion of his explanation illustrate the point.

> "Any movement of the lever L from right to left, or vice versa . . . produces warping which is inverse at the tips of the two lifting surfaces. Any motion of the lever L forward or backward causes . . . a "rotation" of the vertical directional rudder . . . By actuating this lever obliquely, one will obtain <u>simultaneously</u> warping and movement of the rudder."
>
> "We know that warping which causes a [left] bank causes simultaneously a [right] turn . . . "
>
> "To prepare and make a turn to the left: 1) bank to the left by warping the wings and beginning to turn; 2) straighten out the warped surfaces so as not to continue the banking and smartly turn the rudder to the left. To finish the turn: 3) straighten the rudder; 4) level the machine by reversing the previous warping; 5) return the wing surface and the rudder to their neutral states."

The author then notes that in practice, the steps describing initiation and completion of a turn overlap, so the use of warp and rudder deflections are executed more continuously to produce smoother turns.

No contemporaries of the Wrights possessed such a thorough appreciation of the details of turn coordination. Our analyses of the dynamics verify the soundness of the Wrights' concepts for lateral control. The results give us even more respect for their ability to accomplish nearly perfect turns.

8. Concluding Remarks

In 1903, the Wrights understood well the subjects of structures, performance and control. Their structural design is discussed elsewhere in this collection. Their craftsmanship far exceeded that of their contemporaries. Performance is essentially a matter of balancing forces: weight, lift, drag and thrust. The theory required is minimal. But it seems clear from analysis of our wind tunnel data, combined with the documented characteristics of their engine and the 1903 airplane, that the Wrights must have paid much attention to this problem. It is not likely accidental that the geometrical incidence of the wing was set at the angle of incidence for cruise flight. Nor was it a matter of luck that the cruise condition gave them a good margin below stall of the wing.

They had learned from Lilienthal that to design a successful airplane they also had to learn to fly. What they added to that lesson was control, unquestionably their greatest contribution. From the beginning of their work they knew that they had to control rolling and not just pitching as their contemporaries had emphasized. Later they discovered that they also had to control yaw motions. That eventually made the 1903 Flyer manageable.

We have used recent wind-tunnel data and modern theory of stability and control to confirm the Wrights' unparalleled understanding of aircraft control. Solution of the problem of turning was their supreme achievement in flight dynamics and gave them a marketable airplane. Their success required appreciation of aerodynamics and invention of a simple means for the pilot to exercise lateral control with coordinated wing warping and rudder deflection.

There was much the Wrights did not understand well, mainly subjects which were not clarified until many years later. Perhaps the greatest gap in their knowledge was the theory of rotational motions. Without that they could not formulate precise ideas of stability in contrast to equilibrium.

Their 1903 Flyer was severely unstable statically, and barely controllable by modern standards of piloting. They detected the most serious difficulties during flight tests in 1904 and 1905, but could correct them only by trial-and- error: they had no guiding theory. For example, they had deliberately used negatively arched wings to combat the tendency for lateral gusts to force them into the hill while gliding. Our analysis of the dynamics has shown that as a result of the negative dihedral, the spiral mode was so strongly unstable as to be marginally controllable. The Wrights spent nearly a year at Huffman Prairie before they removed the negative dihedral in

1904. They had been treating the instability as a problem of lateral control, but it was in fact a problem of lateral dynamics.

The Wrights' emphasis on control unquestionably flowed from their experience with bicycles. They knew that their airplane need not be inherently stable to be flyable. Their creation of the first practical aircraft proved their principles.

The achievements of the Wright brothers appear more remarkable the deeper we understand their technical work. Their own thorough documentation in letters and diaries makes it possible to interpret their work in the context of modern aeronautics. It is astonishing how rarely they strayed from systematic path to success. What they could not solve with theory and analysis they figured out with systematic testing and carefully evaluated observations. The standards the Wright brothers set as aeronautical engineers remain unsurpassed.

Dedication

Harlan A. "Bud" Gurney (1905-1982) was an extraordinary man: a pioneer of aviation, a pilot his entire life, a supreme source of aeronautical knowledge, a man of impeccable integrity, an inspiration to all who knew him, and a dear friend.

While still a teenager, Bud had supervised construction of Lincoln "Standards," learning the fundamentals of airplane construction from Otto Timm. In 1923 he was in flying school with Charles Lindbergh. Later during their barnstorming days, Bud parachuted from the plane flown by Lindbergh. After nearly four decades with United Airlines, Bud retired in 1968. He had flown aircraft from the Curtiss Jenny to the Boeing 747.

Bud joined the A.I.A.A. Wright Flyer project at a time when we needed his special experience and help. He guided the early construction, much of which he did himself in his garage. He worked with us, he taught us, he regaled us with stories and he is forever at the core of our accomplishments. He admired the Wright Brothers as much as we do. We proudly dedicate this paper to Bud.

Acknowledgments

We thank Mrs. C. Yehle of Caltech for typing the manuscript through many drafts, and Mr. C. Reaber for the great care with which he prepared the figures.

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LIST OF FIGURES

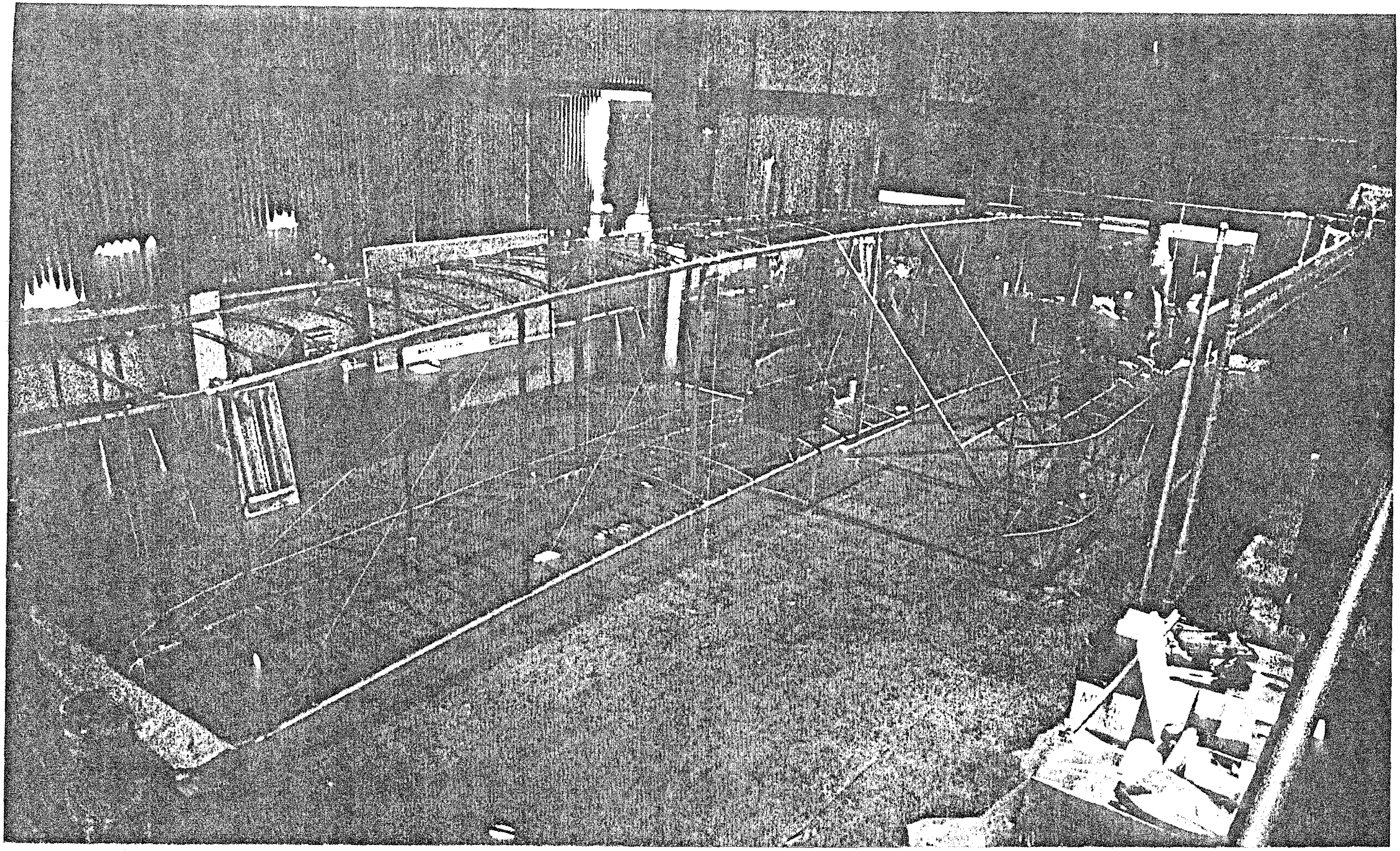


Figure 1. Photographs of the Uncovered Full Scale 1903 Flyer by the AIAA Los Angeles Chapter (1983)

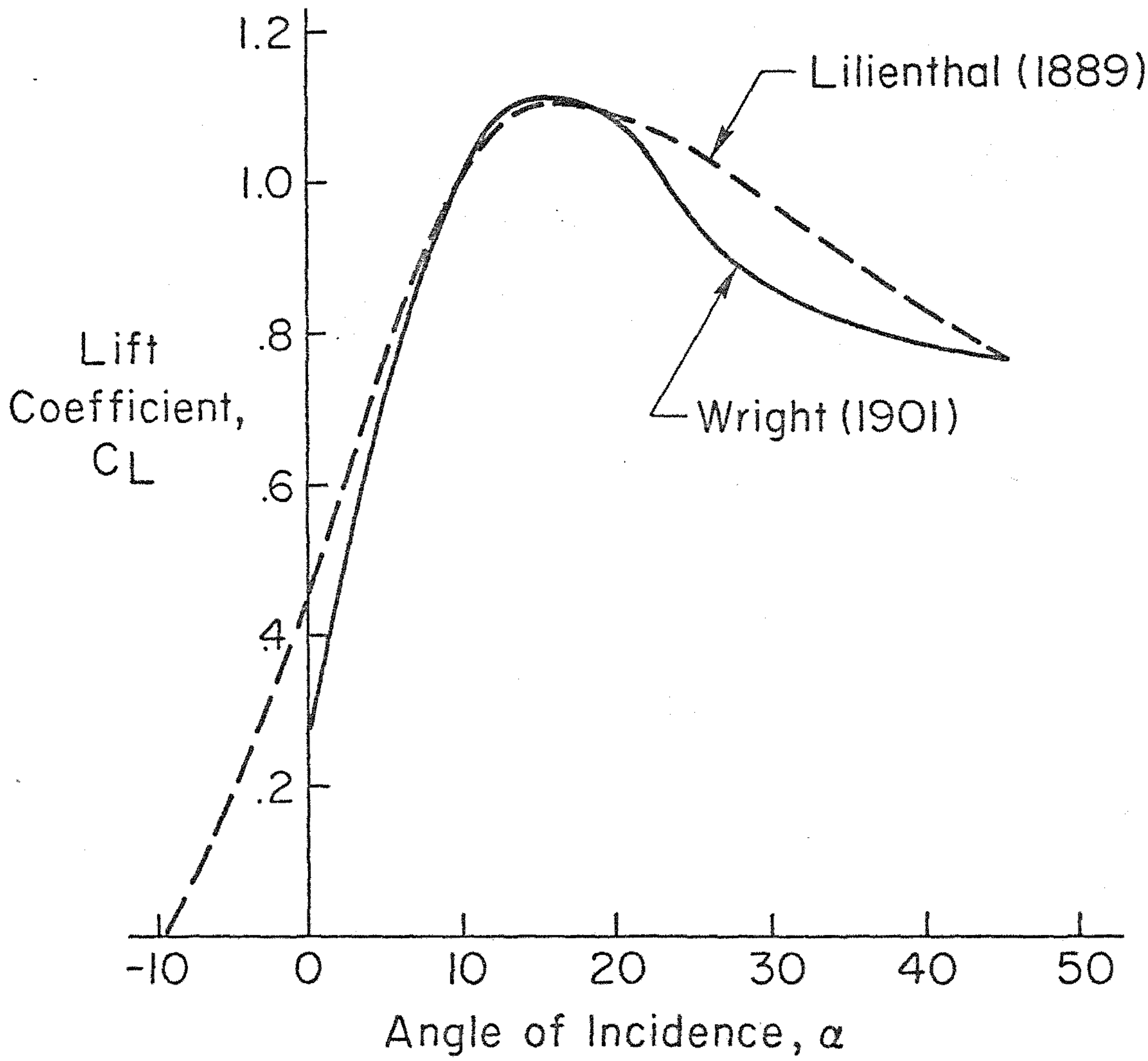


Figure 2. Comparison of Data for Lift Coefficient versus Angle of Incidence; Lilienthal and the Wright Brothers

EQUILIBRIUM(TRIM)   MOMENT = 0

Pitching Moment	$C_m = 0$
Yaw Moment	$C_n = 0$
Roll Moment	$C_\ell = 0$

STABILITY OF EQUILIBRIUM

When a disturbance is applied(e.g. a gust) the change of aerodynamic moment must be such as to restore equilibrum

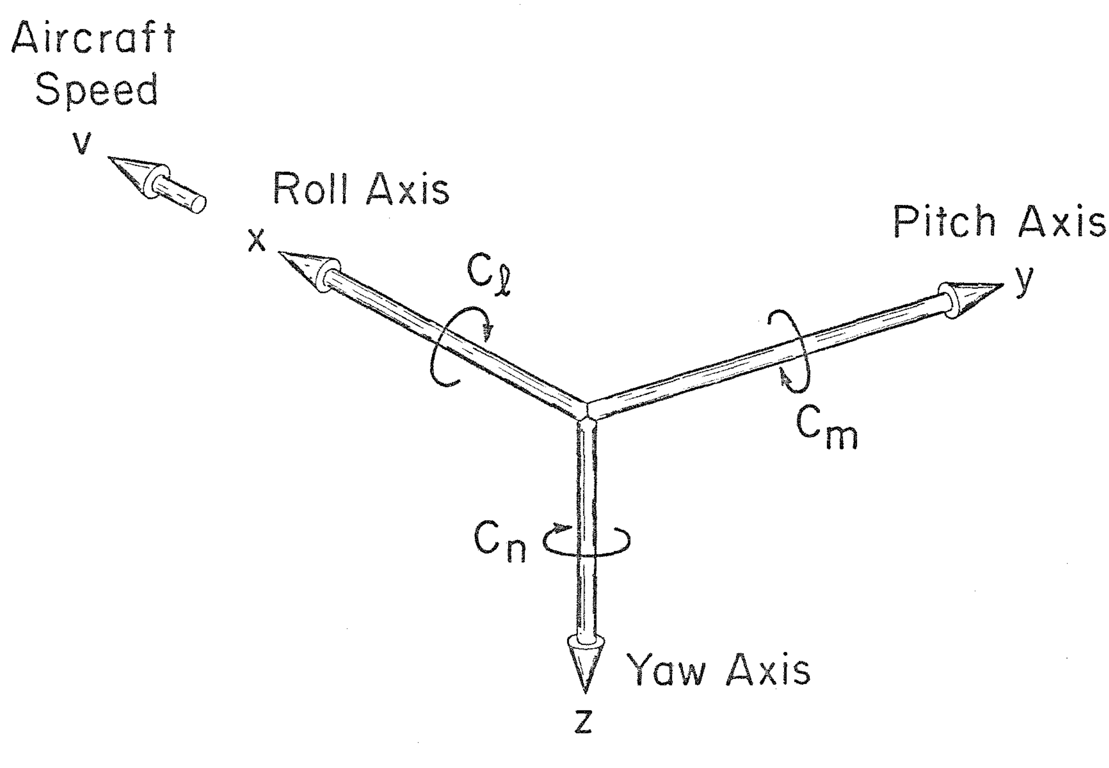


Figure 3. Basic Conditions for Equilibrium and Stability

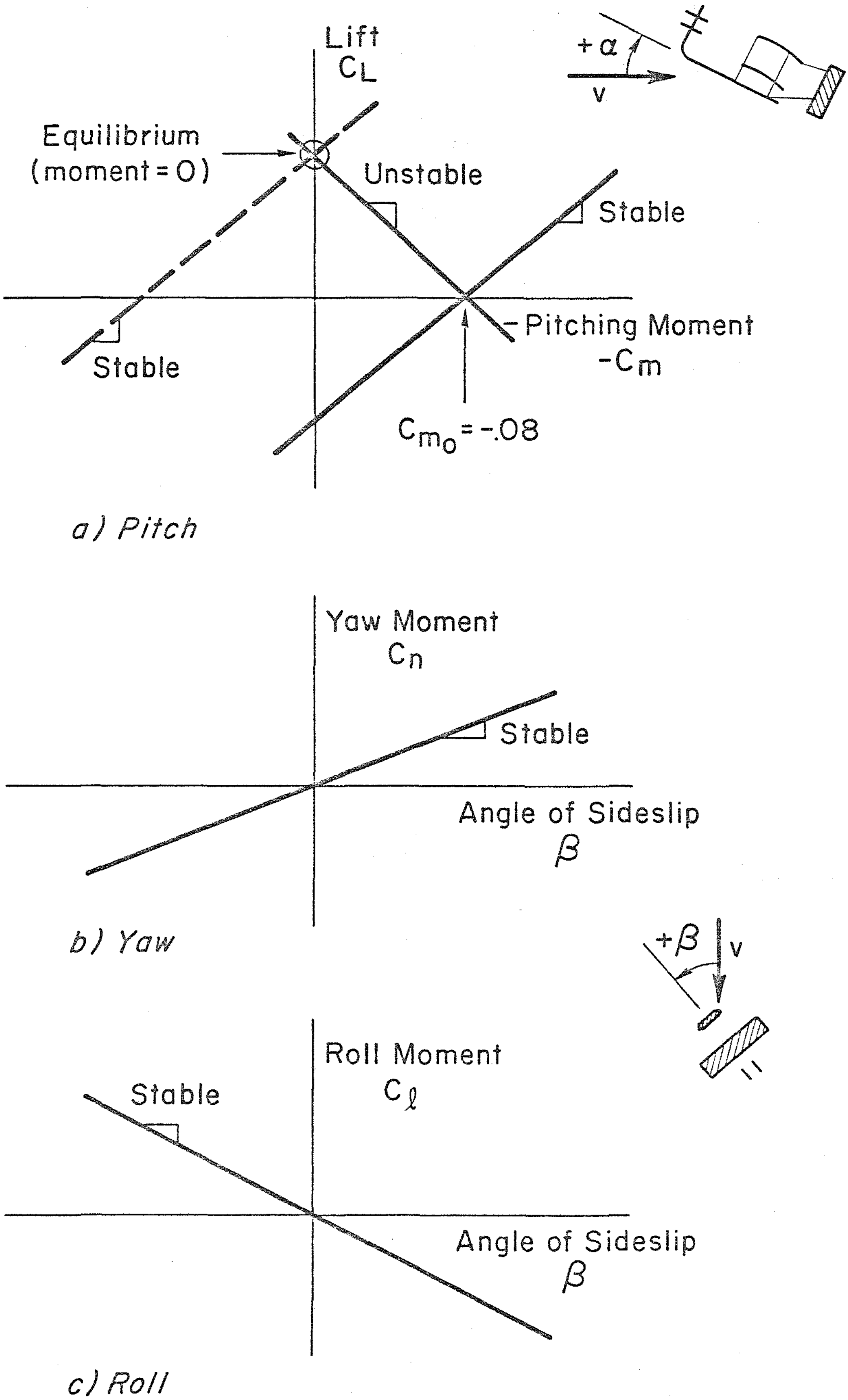


Figure 4. The Three Basic Moment Curves, As Used in Aeronautics

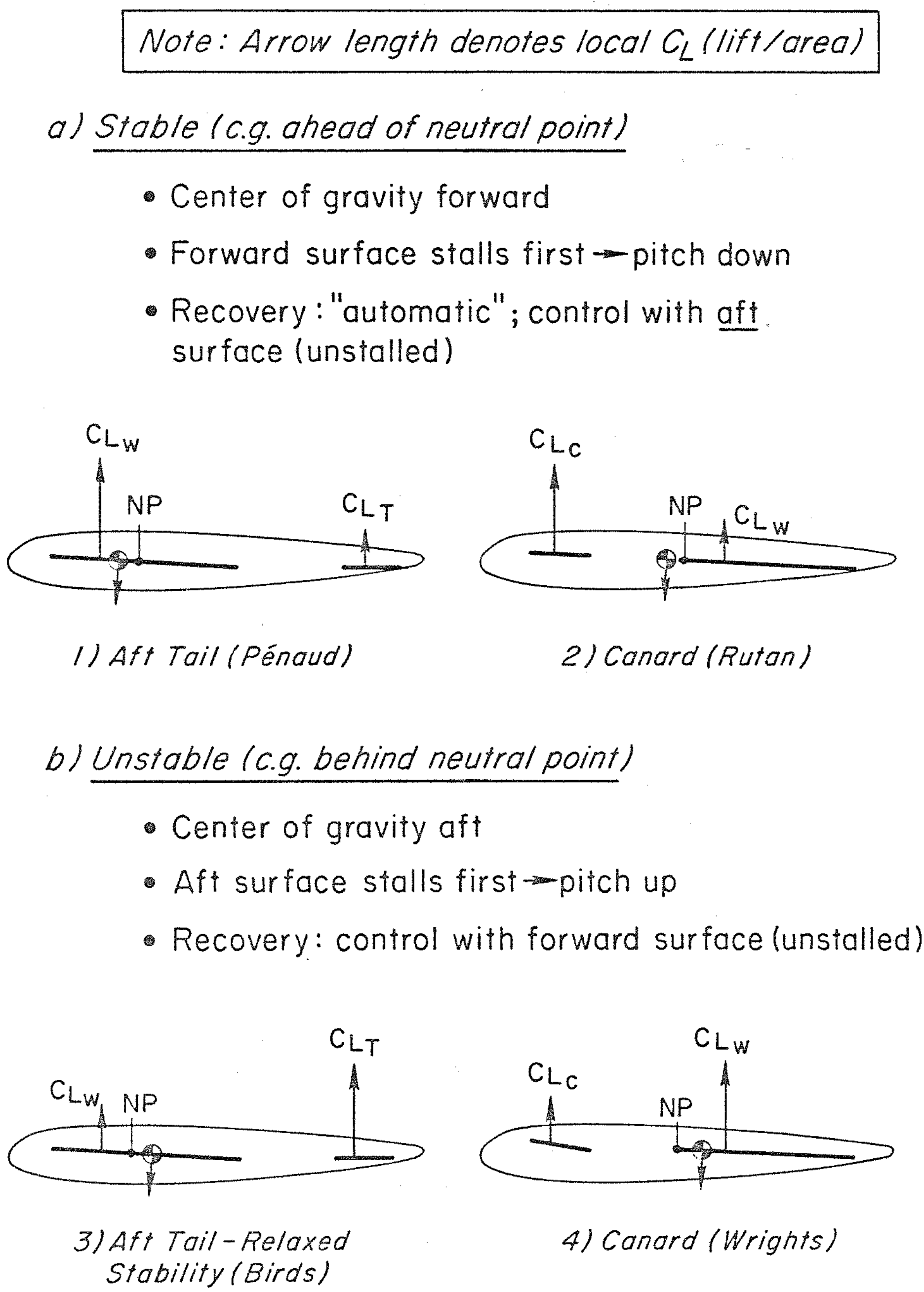


Figure 5. Stable and Unstable Wing/Tail Configurations

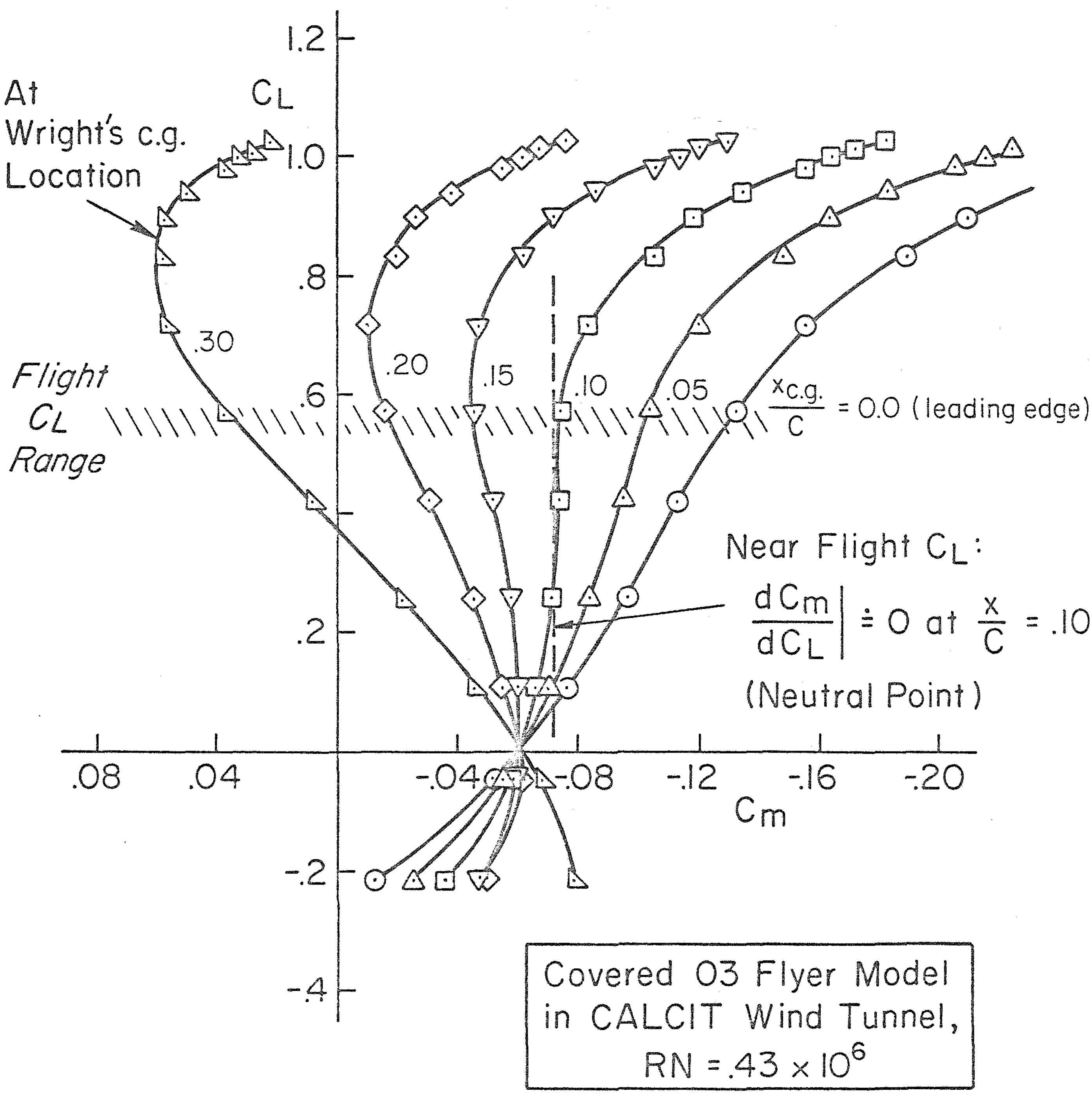


Figure 6. The Influence of the Center of Gravity on the Pitching Moment Curve

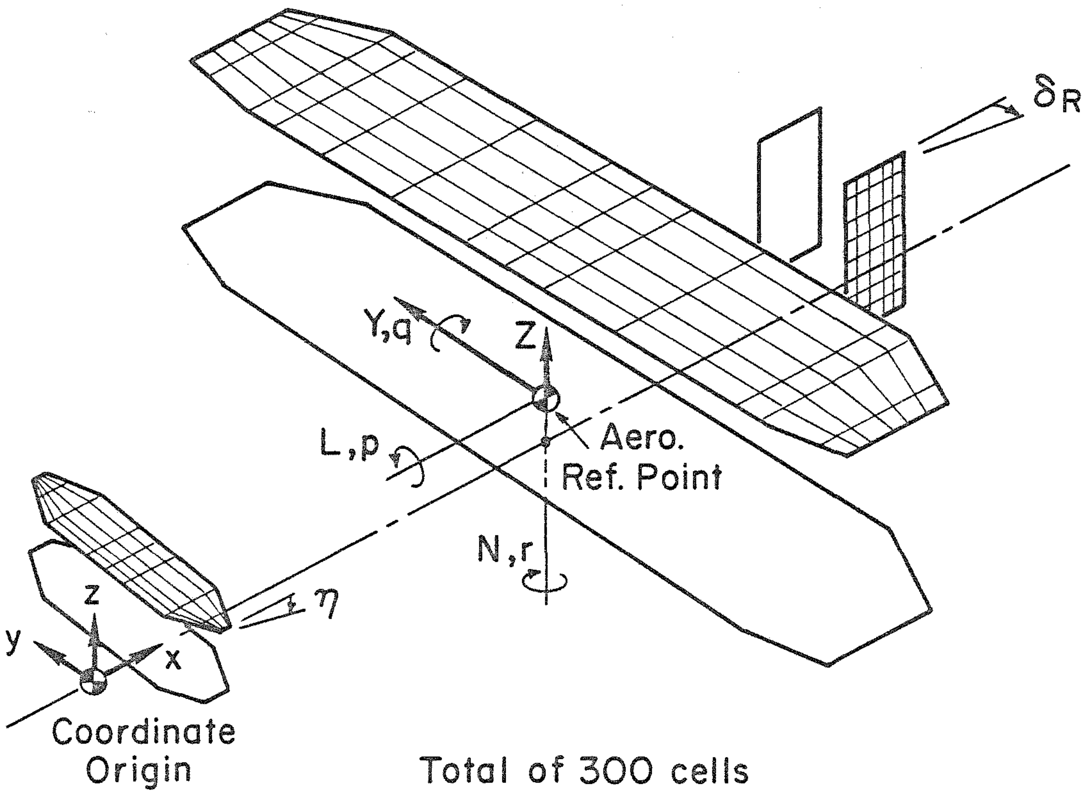


Figure 7. Approximation to the Wright Flyer for Vortex Lattice Calculations

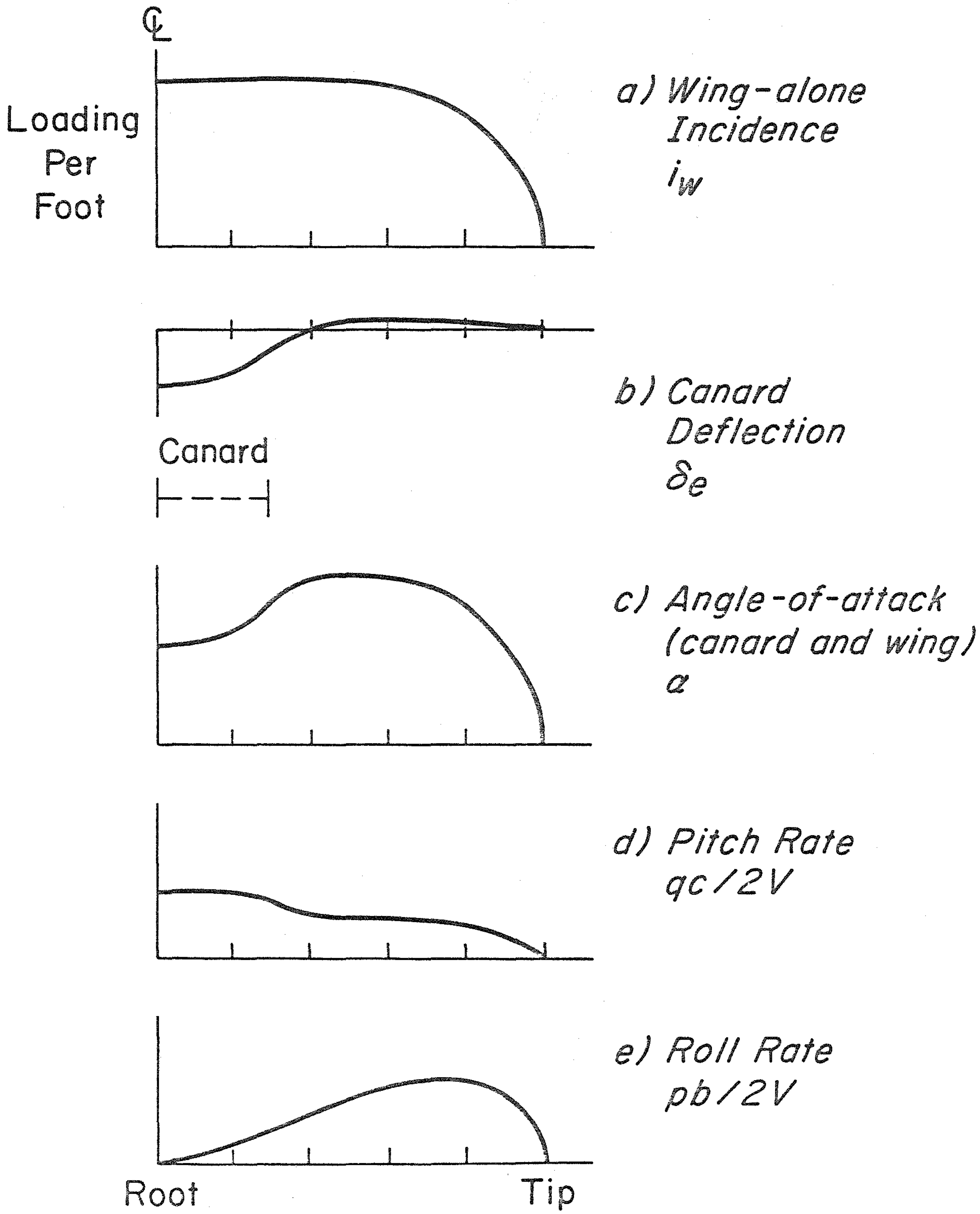


Figure 8. Load Distributions Calculated with Vortex Lattice Theory

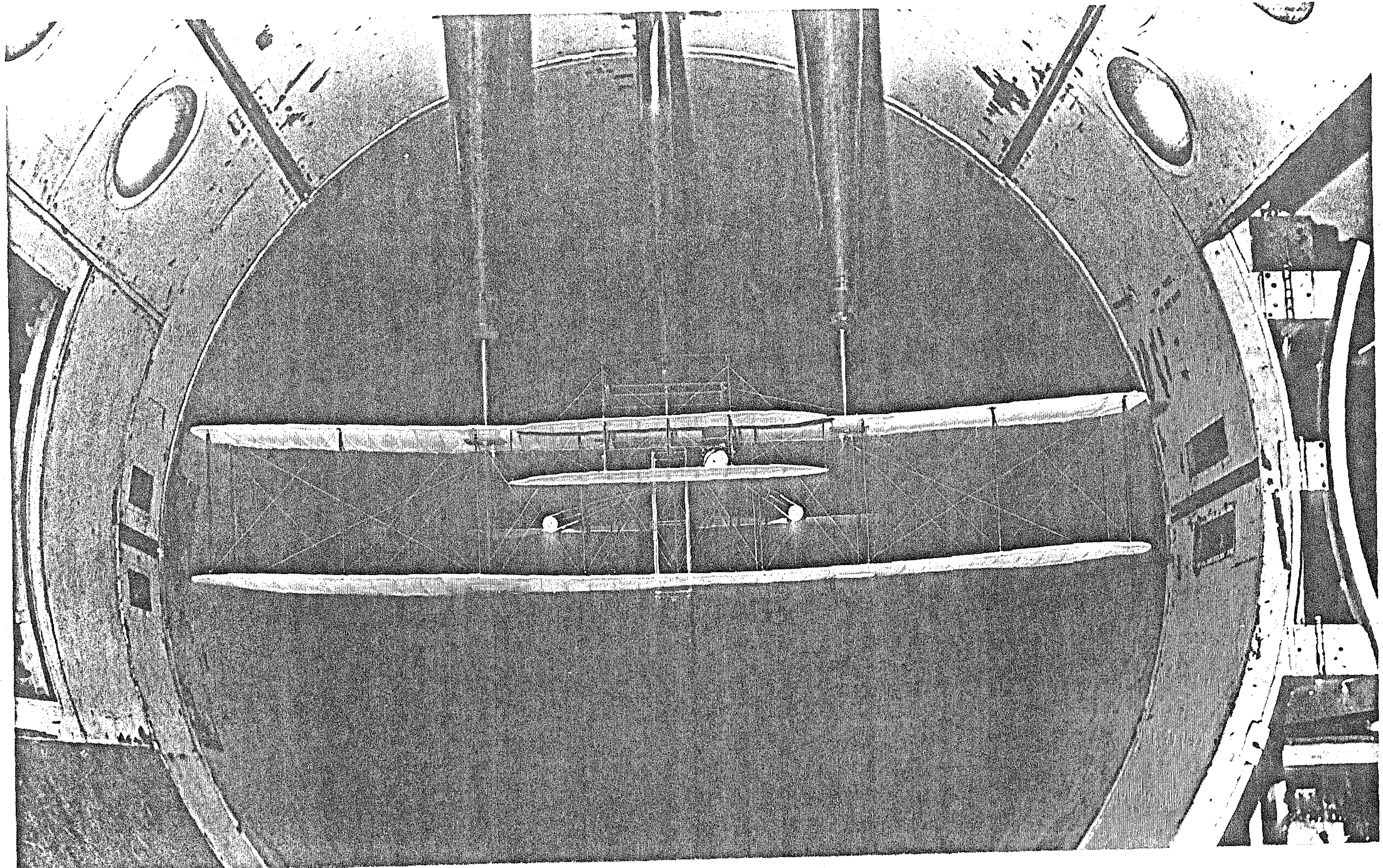


Figure 9. Covered 1/6 Scale Model in the GALCIT Ten Foot Tunnel,
California Institute of Technology

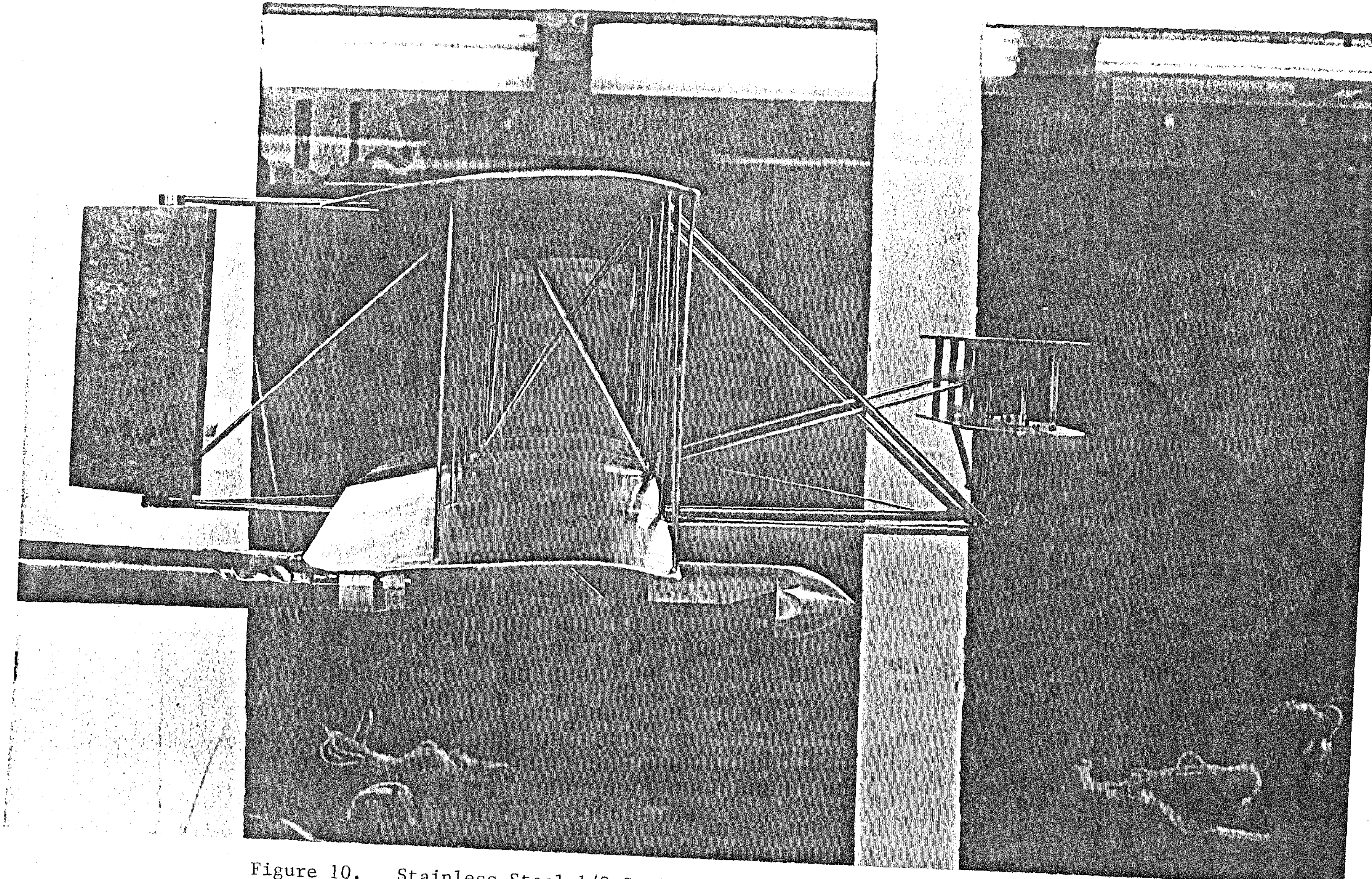


Figure 10. Stainless Steel 1/8 Scale Model in a 7 x 10 foot Wind Tunnel

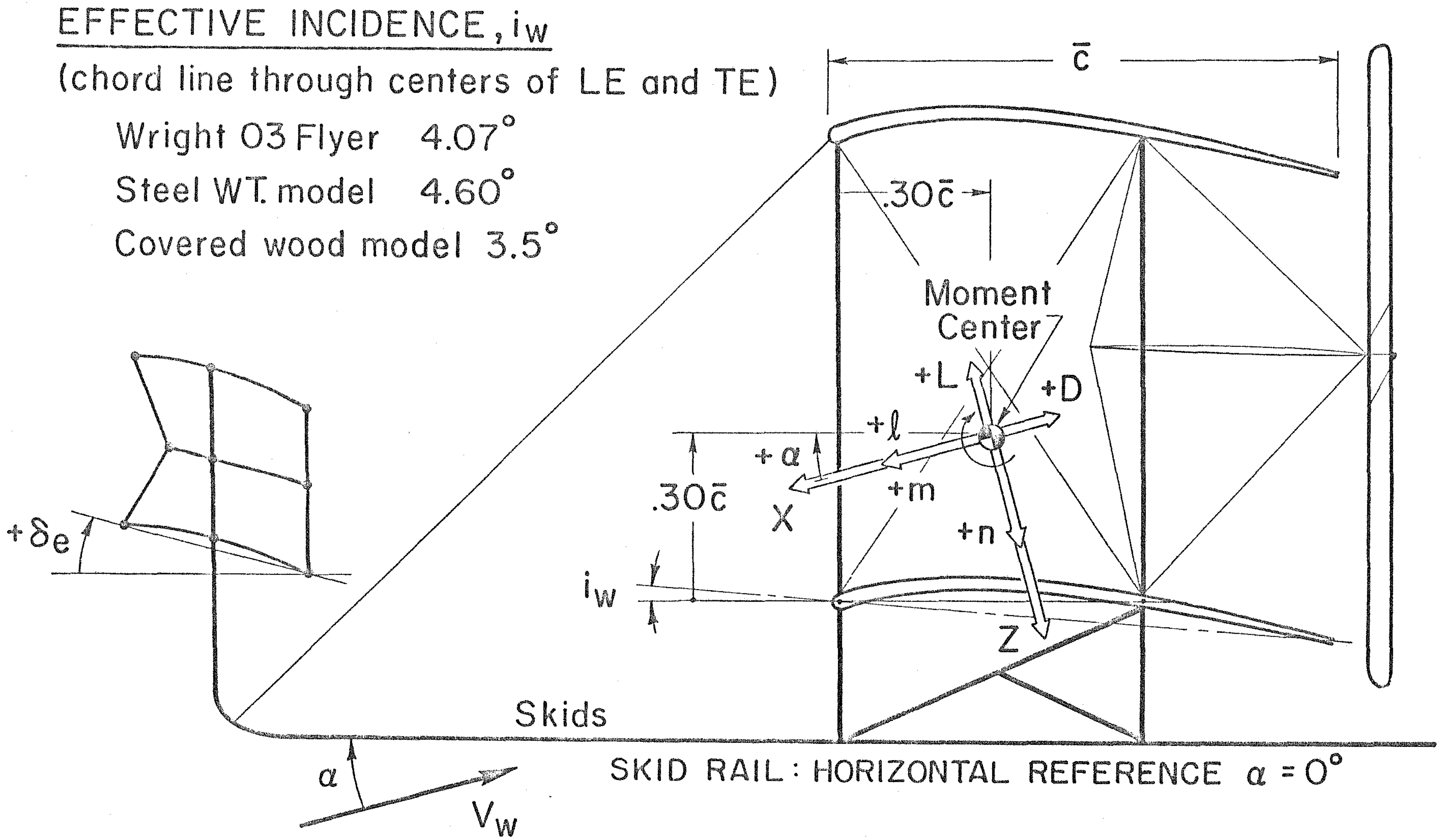


Figure 11. Profile of the 1903 Flyer Showing Reference Lines and Center of Gravity

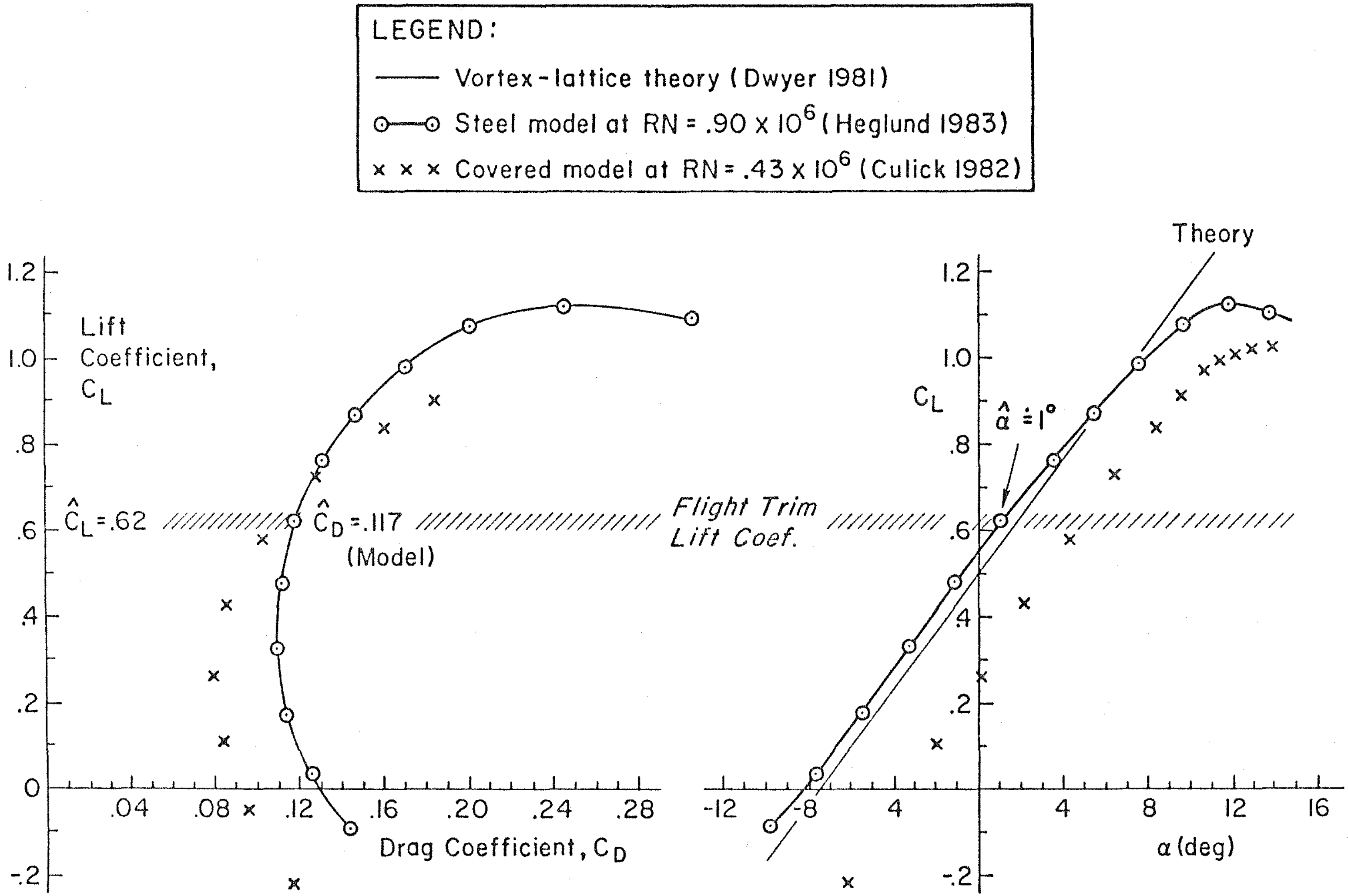


Figure 12. Lift and Drag of the 1903 Flyer; Comparison of Theory and Tests

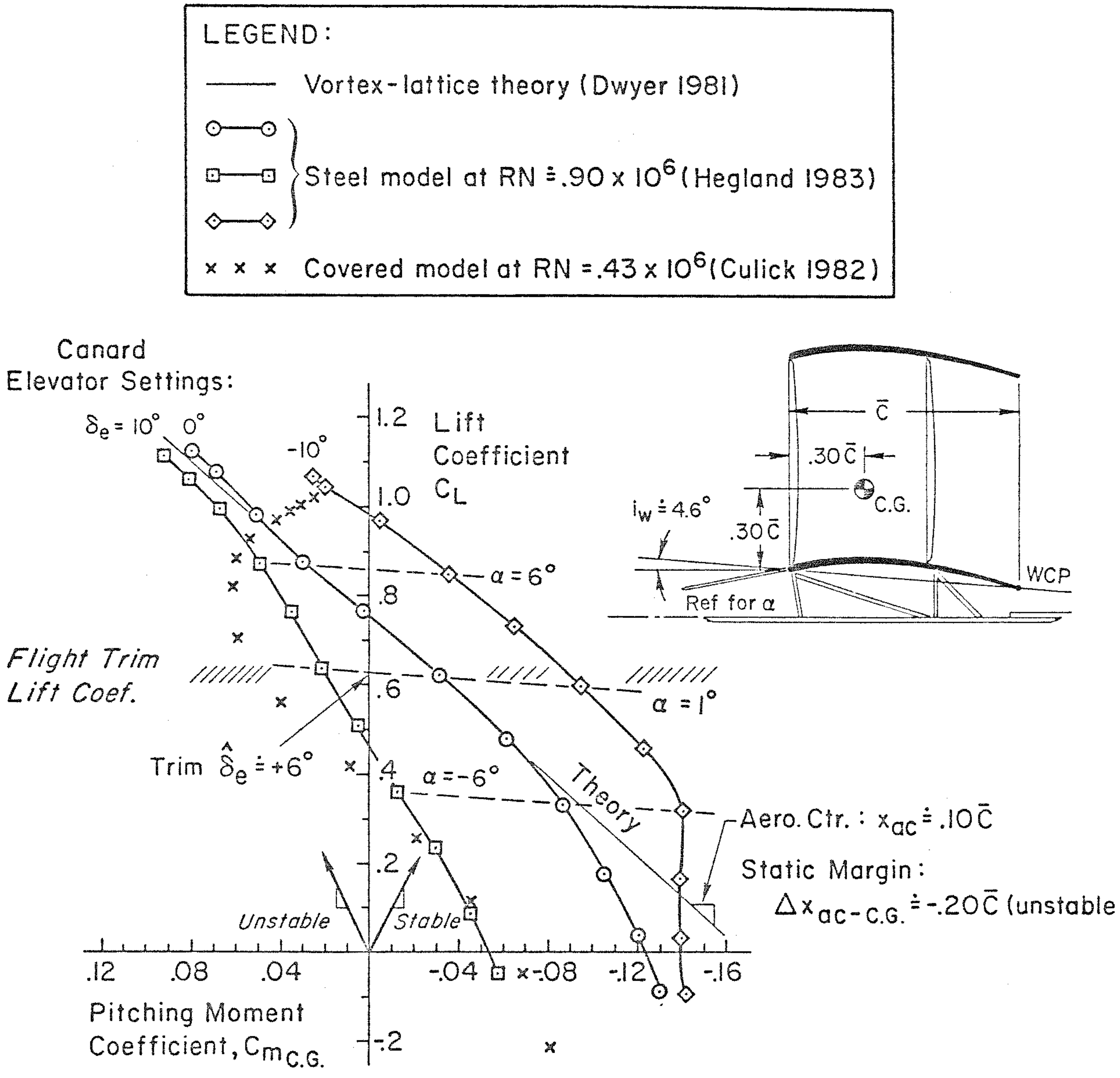


Figure 13. Pitching Moment of the 1903 Flyer; Comparison of Theory and Tests

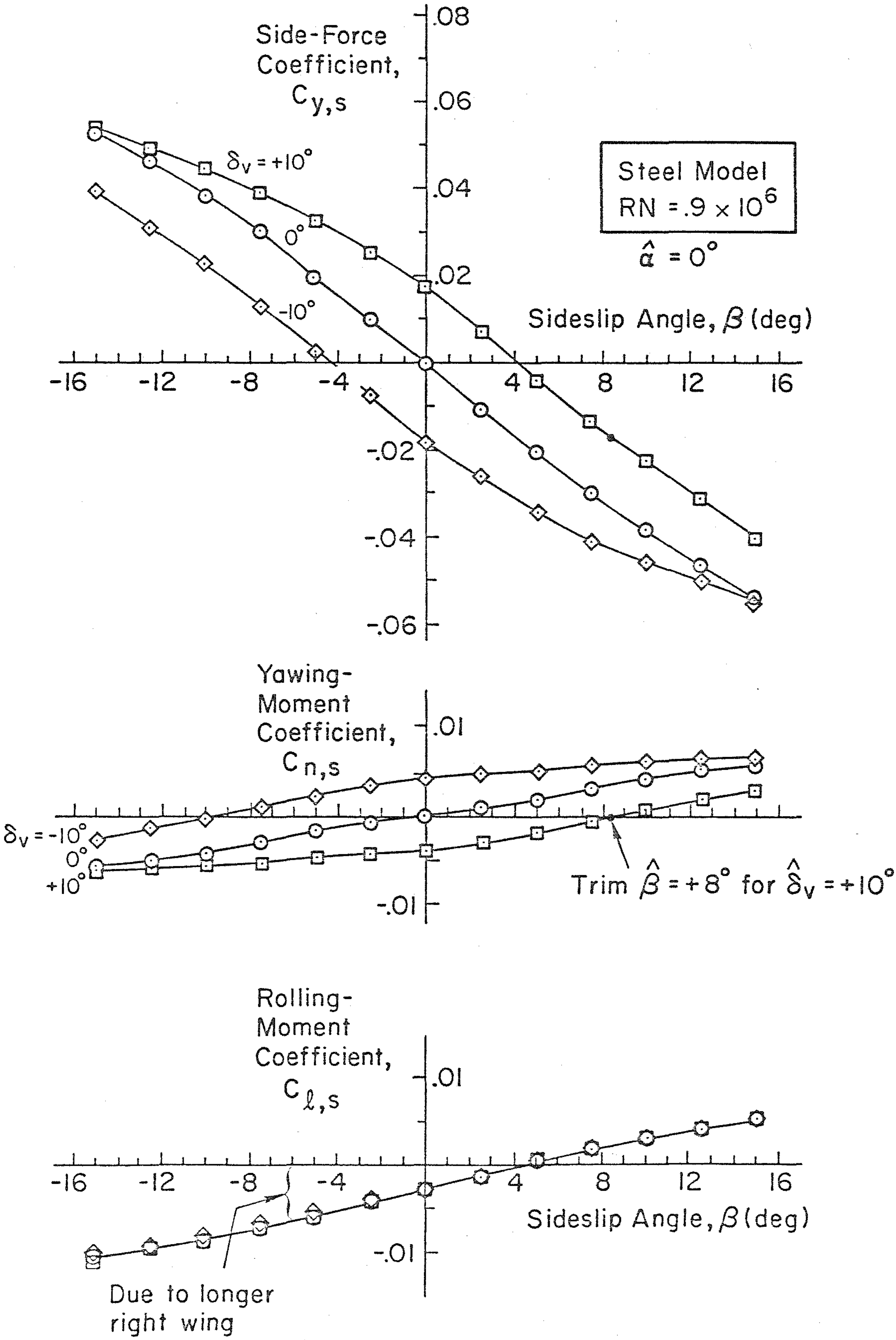


Figure 14. Data for Lateral and Directional Characteristics of the 1903 Flyer at Trim (1/8 Scale Steel Model)

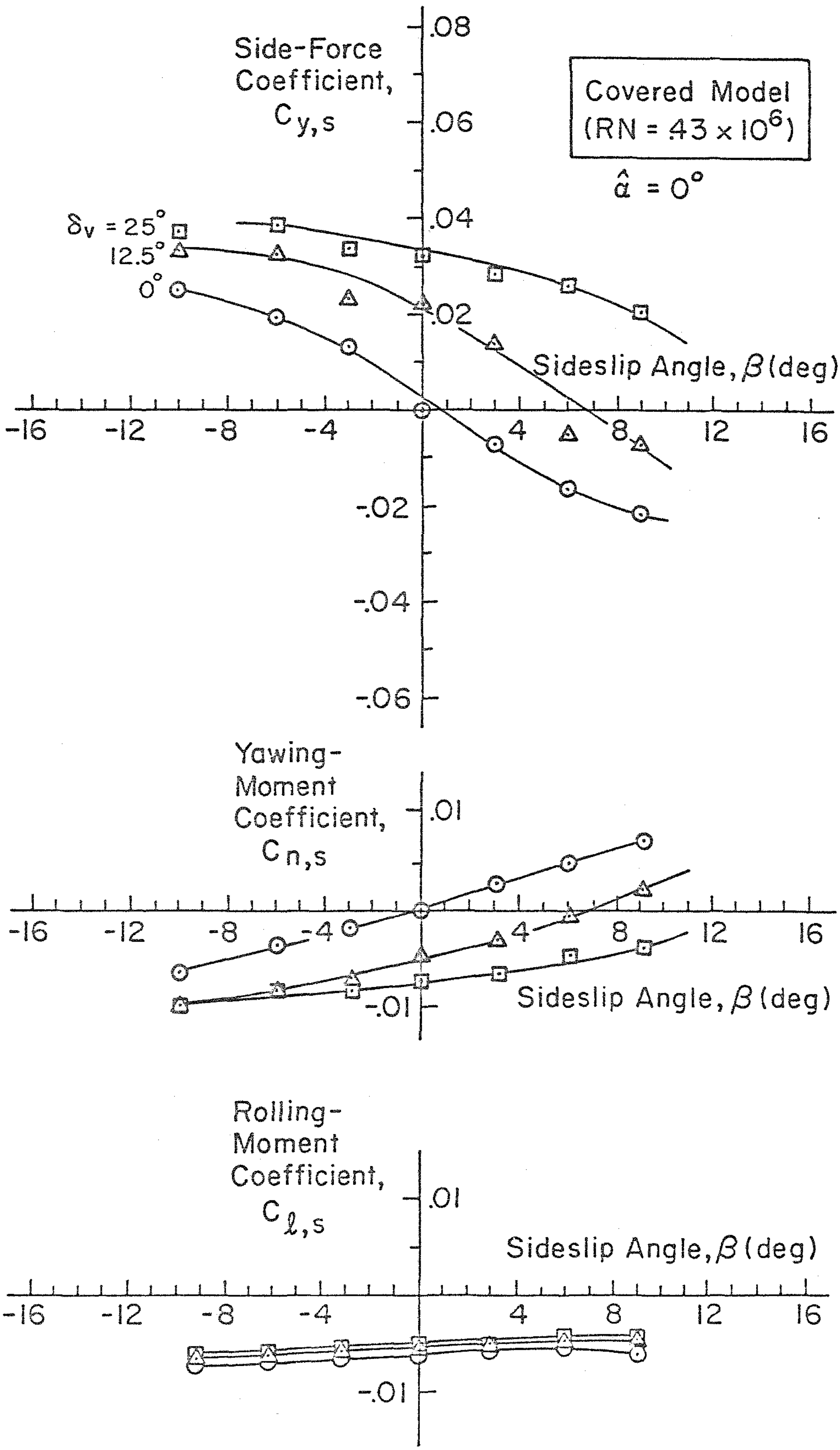


Figure 15. Data for Lateral and Directional Characteristics of the 1903 Flyer at Trim (1/6 Scale Covered Model)

Figure 16. Flight on August 13, 1904: Aircraft Rigged With Anhedral (Plate 84 of Reference 1)

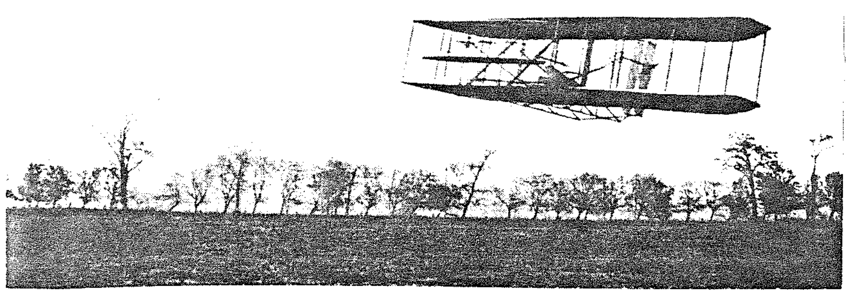


Figure 17. Flight on November 10, 1904: Aircraft Rigged Without Anhedral (Plate 86 of Reference 1)

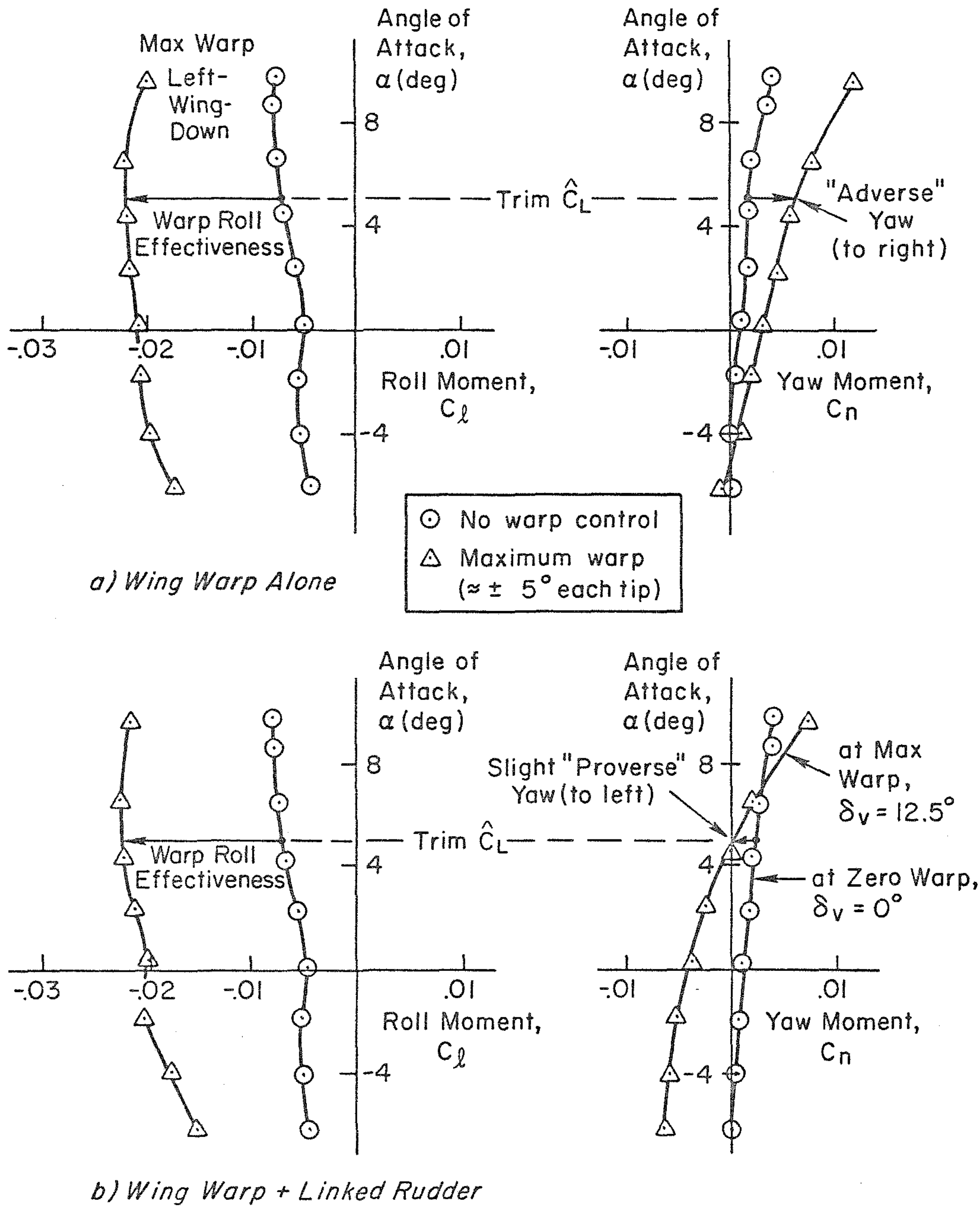


Figure 18. Data for the Lateral Control Effectiveness (1/6 Scale Covered Model), Without and With Linked Rudder

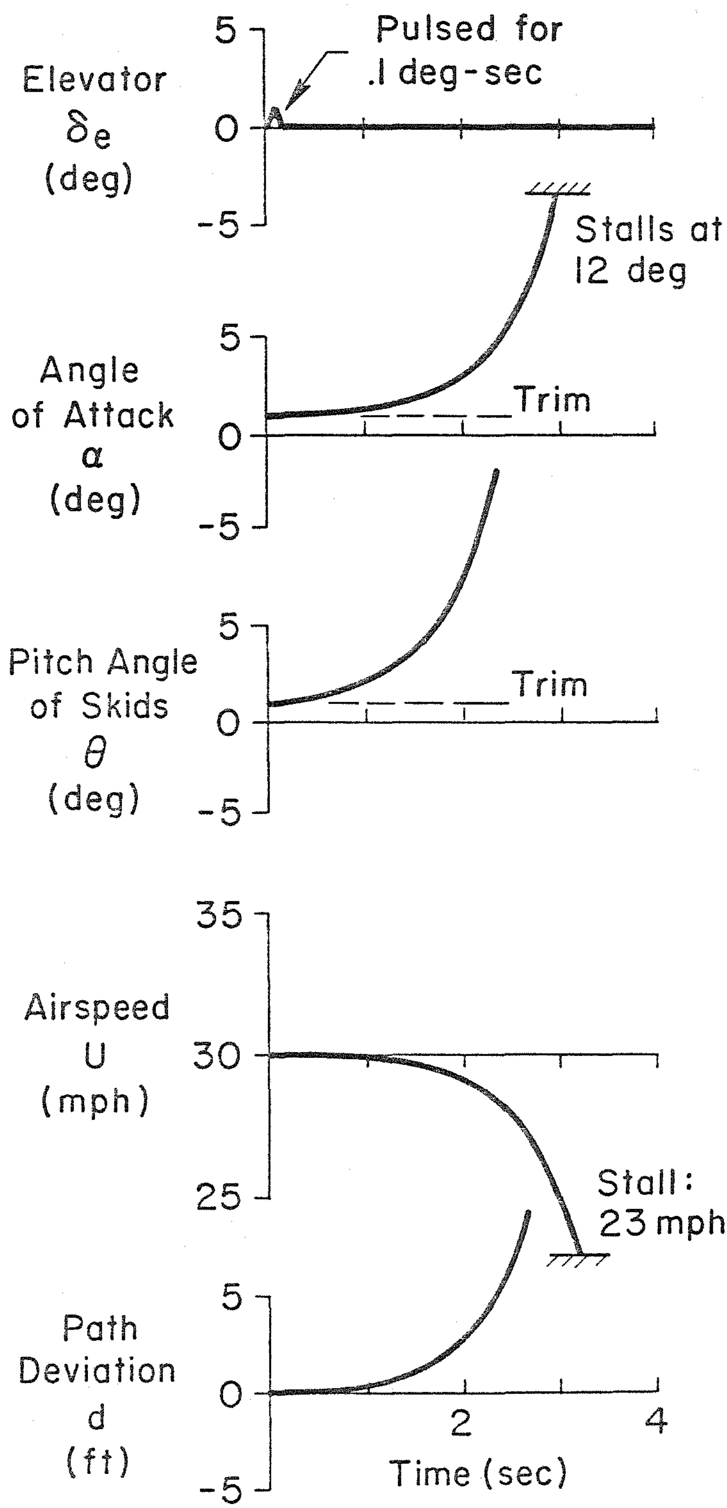


Figure 19. Open Loop Time Response in Pitch; One Degree Second-Pulsed Canard Deflection

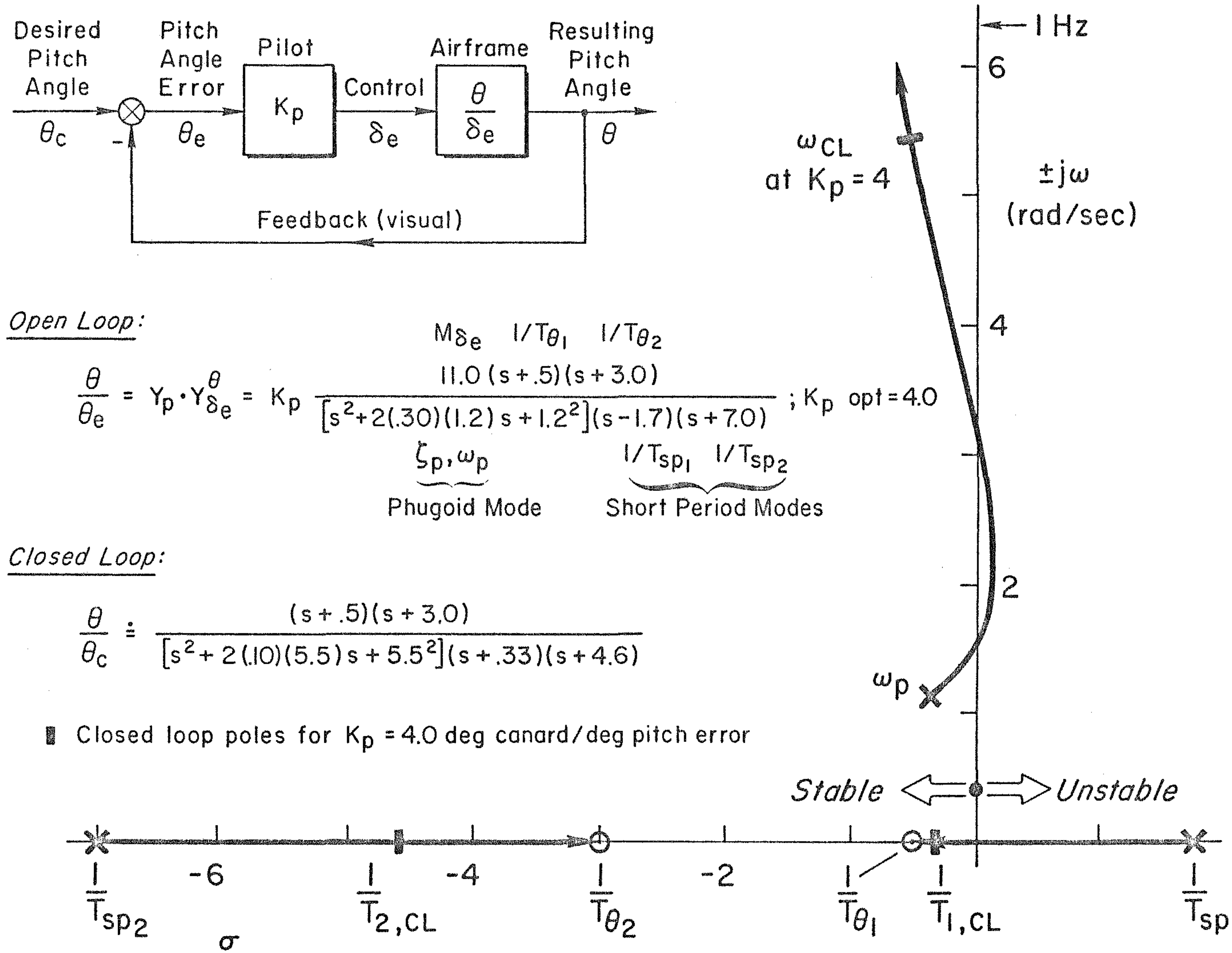


Figure 20. Locus of Dynamic Roots for a Pilot Control Law with Canard Deflection Proportional to Pitch Angle Error

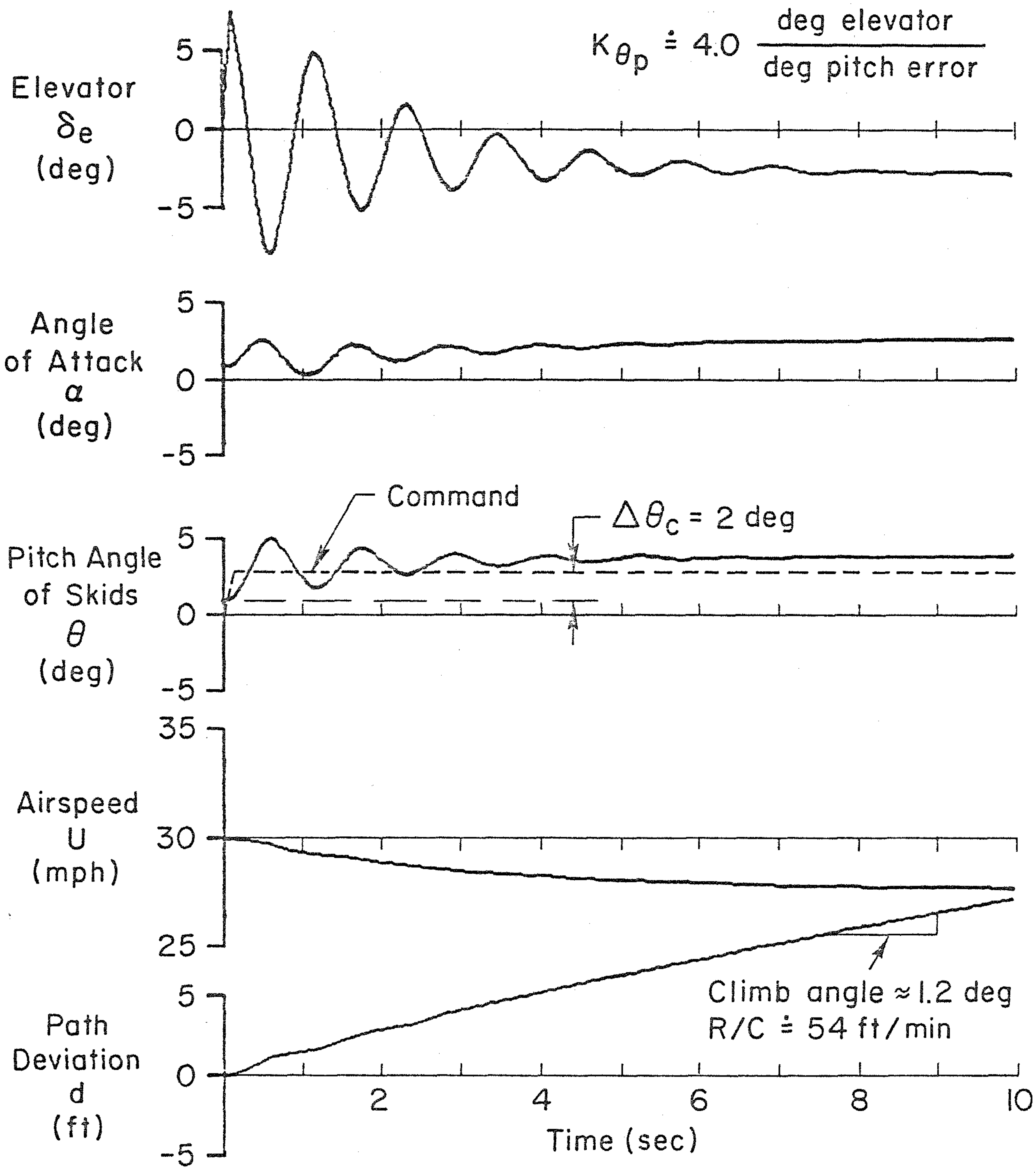


Figure 21. Piloted (Closed Loop) Longitudinal Time Responses to Two Degrees of Pitch Command

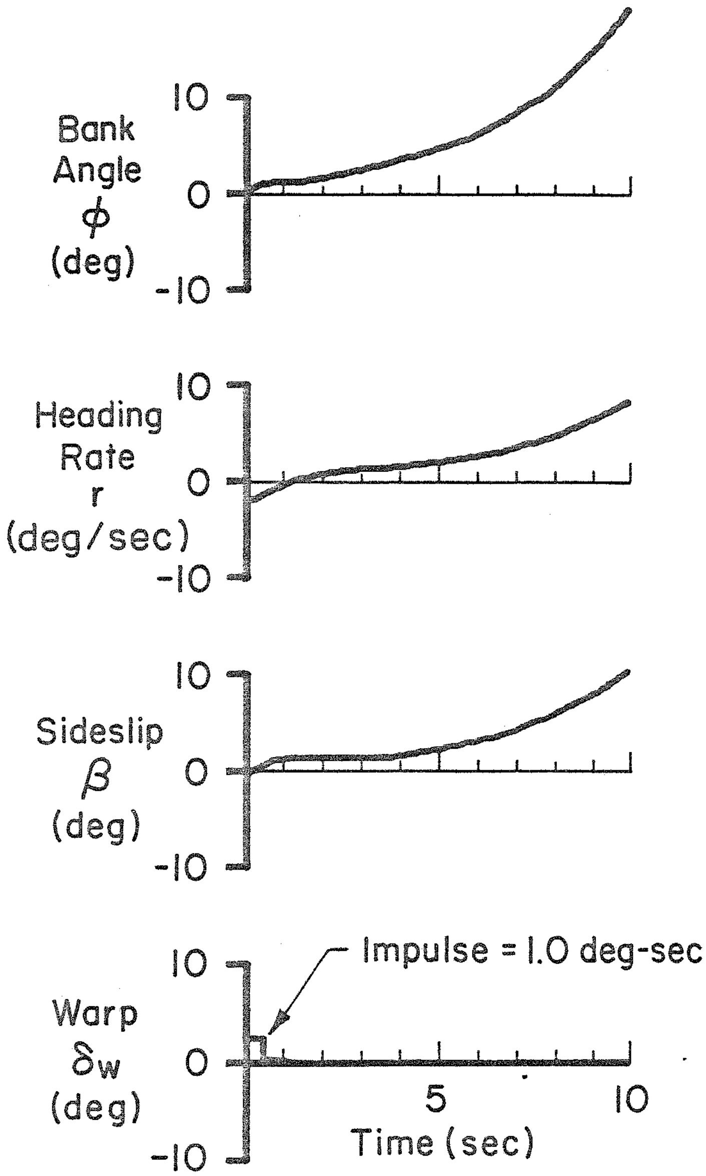
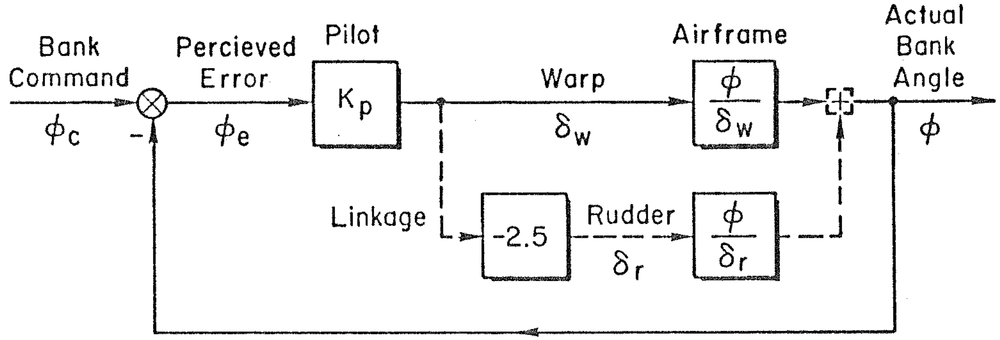


Figure 22. Open Loop Lateral Responses to a Wing Warp Pulse

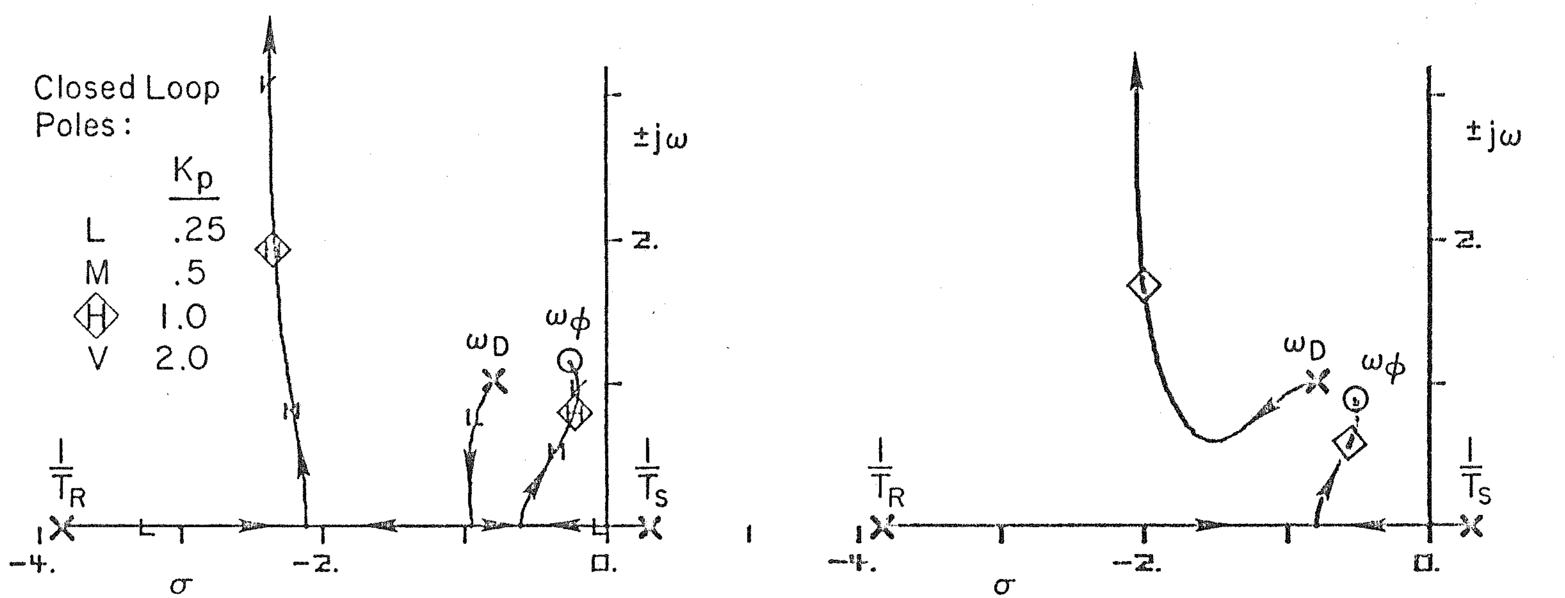


Open Loop (pure warp):

$$\frac{\phi}{\phi_e} = Y_p \cdot Y^{\theta}_{\delta_w} = K_p \cdot \frac{\overset{L_{\delta_w}}{5.9}\ \overset{\zeta_\phi\quad \omega_\phi}{[.005, 1.3]}}{\underset{1/T_S}{(-.3)}\underset{1/T_R}{(3.8)}\underset{\zeta_{DR}\quad \omega_{DR}}{[.6\ ,\ 1.3]}}$$

Open Loop (warp + linked rudder):

$$\frac{\phi}{\phi_e} = K_p \cdot \frac{5.8\ [.47, 1.2]}{(-.3)(3.8)[.6\ ,1.3]}$$



a) Warp Alone

b) Linked Rudder ($\delta_r = -2.5\,\delta_w$)

Figure 23. Locus of Dynamic Roots for a Pilot Lateral Control Law With Warp Deflection Proportional to Bank Angle Error

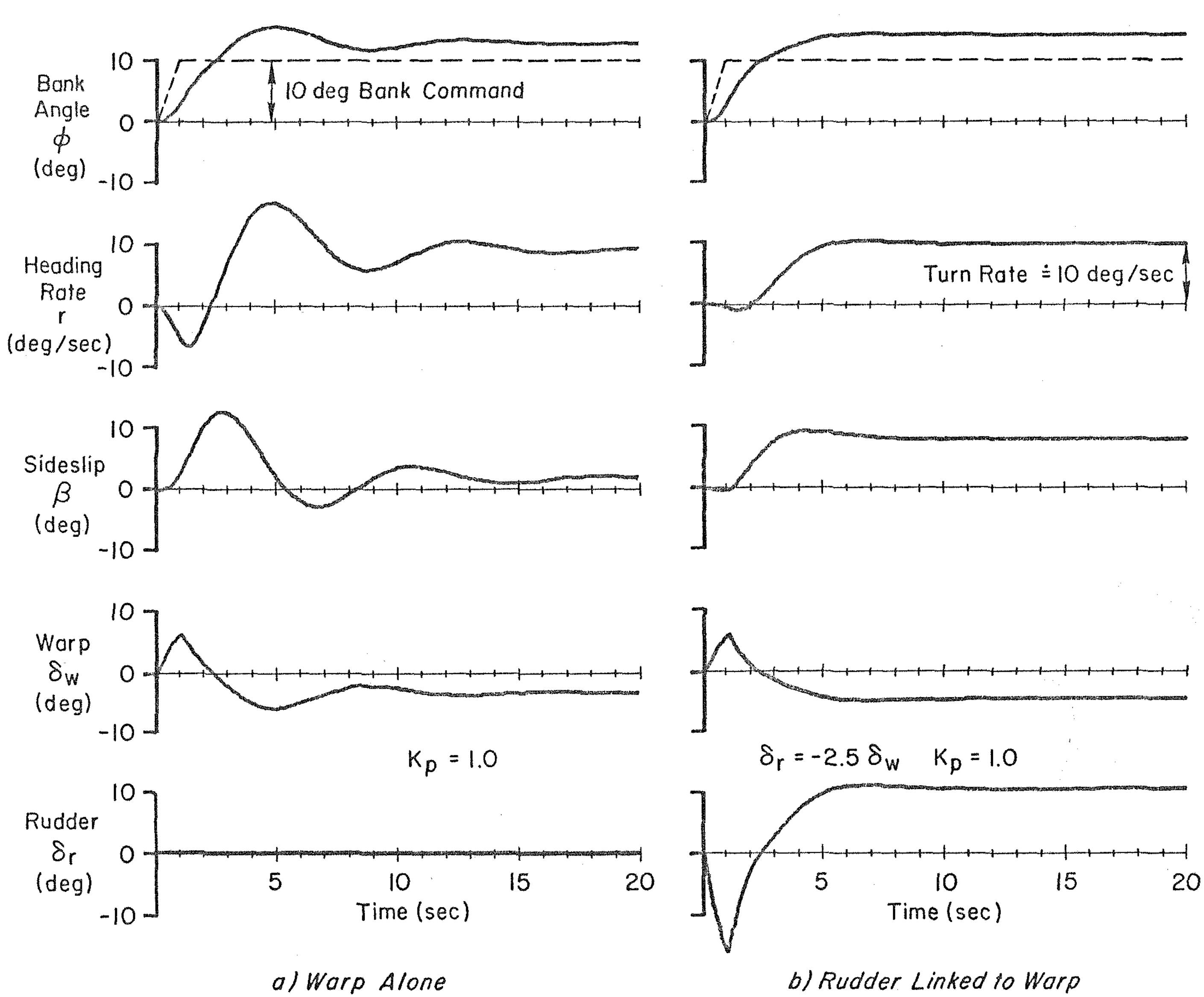


Figure 24. Piloted Time Responses to a Ten Degree Banked Turn Command